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PERIODIC INTERANNUAL VARIATIONS OF MIDWESTERN
UNITED STATES TEMPERATURES IN DECEMBER

BY
DOUGLAS CARL PEARSON
CAPT
USAF

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
(Meteorology)

at the
UNIVERSITY OF WISCONSIN - MADISON

1982

76 pages

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Three strong periodicities are observed in the time series of December temperature at St. Cloud Minnesota (1893-1980). These three frequencies (.3868 cycles/year, .2263 cycles/year, and .1132 cycles/year) are shown to have a time and space "sensitivity". December is a sensitive time because synoptic flow patterns are transitional from a fall regime (i.e. a Gulf of Alaska low) to a winter regime (i.e. an Aleutian low). The north-central United States is a sensitive area because mean air mass confluence zones (i.e. stronger temperature gradients) lie in and near this region in December. A periodic shifting of the pressure pattern ("forcing") should result in similar periodic changes in the temperature pattern ("response") in sensitive locations near strong mean temperature gradients. This hypothesis is tested using temperature data across the United States and Canada. Because temperature patterns are related to synoptic pressure patterns, pressure data (1899-1978) are examined for analogous frequencies. The results indicate that the region of northwest Canada may "force" a "response" in temperature data 2600 km to the southeast. Because December temperature and pressure data are dominated by two or three strong periodicities, and justifiable synoptic explanations exist for the observed association of temperature and pressure, year-in-advance forecasts are made on twenty years of independent data using regression techniques. Two-by-two skill scores of .30 or greater are found in a large region in and near the air mass confluence zones.

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LIST OF SYMBOLS

T = temperature
 \bar{T} = mean temperature
 A_1 = amplitude of cosine function
 f = frequency
 f_a = alias frequency
 f_h = frequency higher than the Nyquist frequency
 t = time in years
 A_2 = amplitude of sine function
 P = pressure
 \bar{P} = mean pressure
 A = amplitude
 B = denormalized amplitude
 ϕ = phase angle
 Δt = sampling period
 A_h = amplitude of harmonic
 ϕ_h = phase angle of harmonic
 C = number of forecasts correct
 E = number of forecasts correct by chance
 F = total number of forecasts
 j = number of Fourier cycles
 N = total number of years
 f_j = frequency of the j^{th} Fourier cycle
 σ = standard deviation

INTRODUCTION

Modern society faces many problems in the decision making process. Weather affects all segments of our society and reasonably accurate, one to three year, long range forecasts would be helpful for decision making in a growing number of diverse operations. A long range forecast can be a useful aid for predicting such things as agricultural production, food exports or imports, construction and load requirements for utilities, production quotas for weather related industries (i.e. air conditioners, snow blowers, etc.), energy demands, and even the climatic impact on our economy or stock market. The goal of climatic prediction is to make usefully accurate long range forecasts to meet these needs and this study will contribute to that goal.

Several different approaches have been used in the attempt to make long range predictions. Forecasts have been made using general circulation models, statistical models, and analogue techniques. Most of these methods perform poorly for year-in-advance forecasting, and marginally (if at all) for month-in-advance forecasts.

The approach used here concentrates on the periodic behavior of climate. There is significant evidence of cyclic patterns in temperature, precipitation, and pressure data. If a pattern consistently repeats itself and is forced by a physical mechanism, either mechanical or thermal, then the resulting cycle can be used as a forecast tool. Cycles in climatic data have been studied in a wide range of time scales (Fig. 1). The daily cycle (365 cycles/year) and

the annual cycle (1 cycle/year) are well known in climatological data. Both of these cycles have thermal and mechanical forcing mechanisms. Using the annual cycle, a forecast can easily be made that January will be colder than July in most of the Northern Hemisphere. A useful long range forecast requires a prediction which compares the forecast value to the mean value for a specific month; for example, this January will be colder than the mean or normal January. Thus, predicting interannual variability is the key to long range forecasts and this involves forecasting interannual fluctuations about the mean.

With the ultimate application (prediction) in mind, this study will concentrate on periodicities which are well defined and have regional consistency. The time series of December temperatures in the upper Midwest will be analyzed for answers to the following questions. What periodicities are observed in the December temperature data in the upper Midwest? Why is there such a strong periodicity in December temperature data? Does this periodicity have a synoptic explanation or is it a random feature of climatic variability? Will such cycles continue in the future because of a link between physical causes and their effects on the earth-atmosphere system? And finally, is this approach a useful forecast aid? The examination of December temperature data provides the first evidence for periodicity. By extending the study to pressure data, an internal consistency between temperature and pressure data is demonstrated. Verification of forecasts made with this technique will be presented.

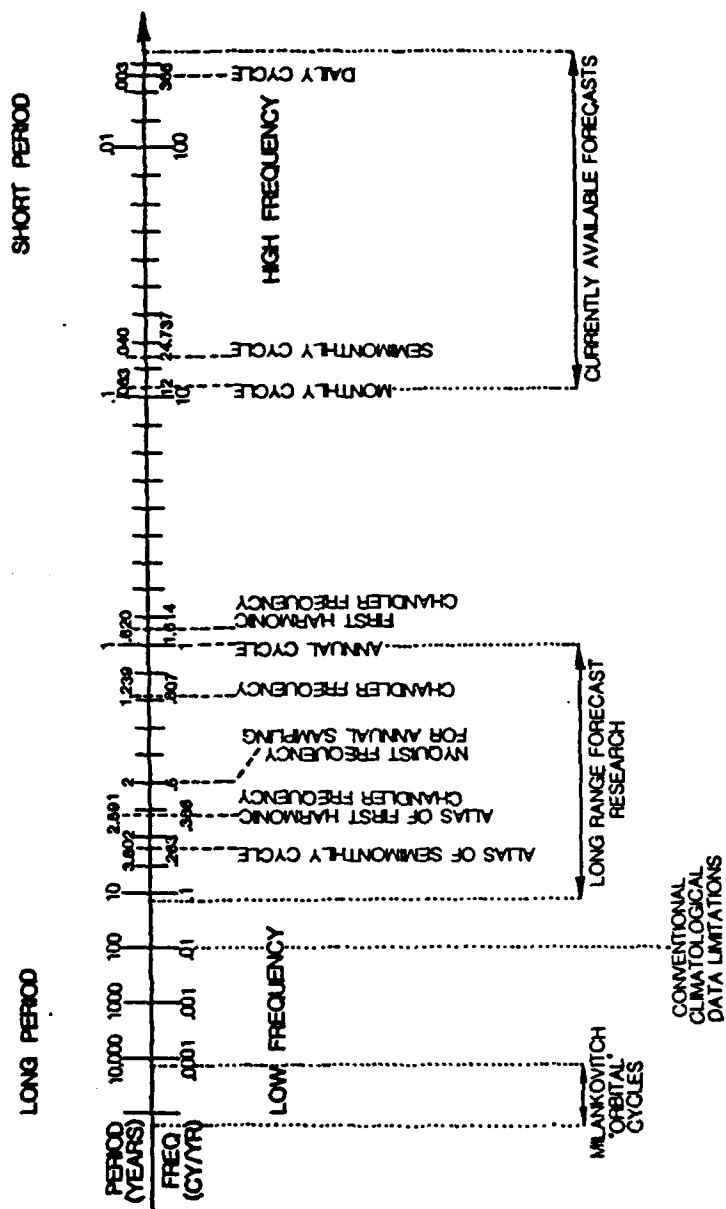


Figure 1. Time scales of climatic cycles.

TEMPERATURE ANALYSIS

A variance spectrum or periodogram of a time series indicates the distribution of variance as a function of frequency (period). Of course all periods appear to be present equally in random data so we must ask whether in any particular time series, there are a few periodicities whose importance is significantly greater than that expected of random data. Because temperature, precipitation and pressure are meteorological parameters with the best and longest records, frequencies in these records were examined as possible indicators of forcing mechanisms in the atmosphere. Variance spectrum analysis of 64 stations (see Appendix) across the United States showed a few strong periodicities in December temperature data in the upper Midwest. In a large portion of the upper Midwest 20%-30% of the variability in mean December temperatures can be accounted for by adding the percent variance of bands 38 and 39 (Fig.2). Bands 38 and 39 correspond to frequencies .38 cycles/year and .39 cycles/year using a 100 year record length. The strong signal at these bands represents approximately ten times more variance than what would be expected by chance. This signal seems to be strongest in Minnesota. The sharp signals in December temperature data will be analyzed and investigated for their predictive capabilities.

The strong signal at St. Cloud in central Minnesota (Fig. 2) provides a logical direction for investigation of the St. Cloud December temperature record (1893-1980). The variance spectrum of the

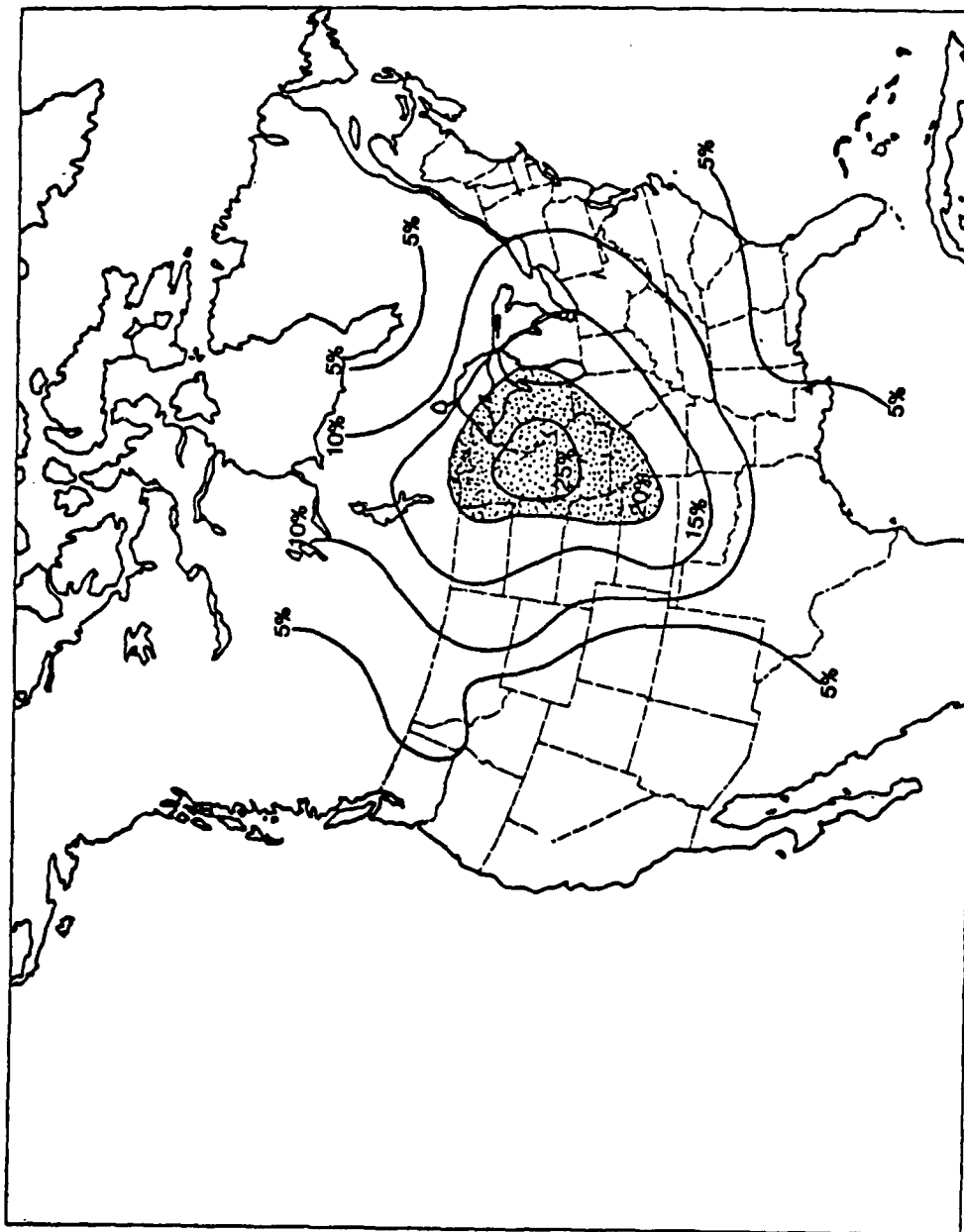


Figure 2. Variance of mean monthly December temperatures explained by bands 38 and 39. Obtained from 100 year spectra calculations. Shaded area represents explained variance of 20% or more.

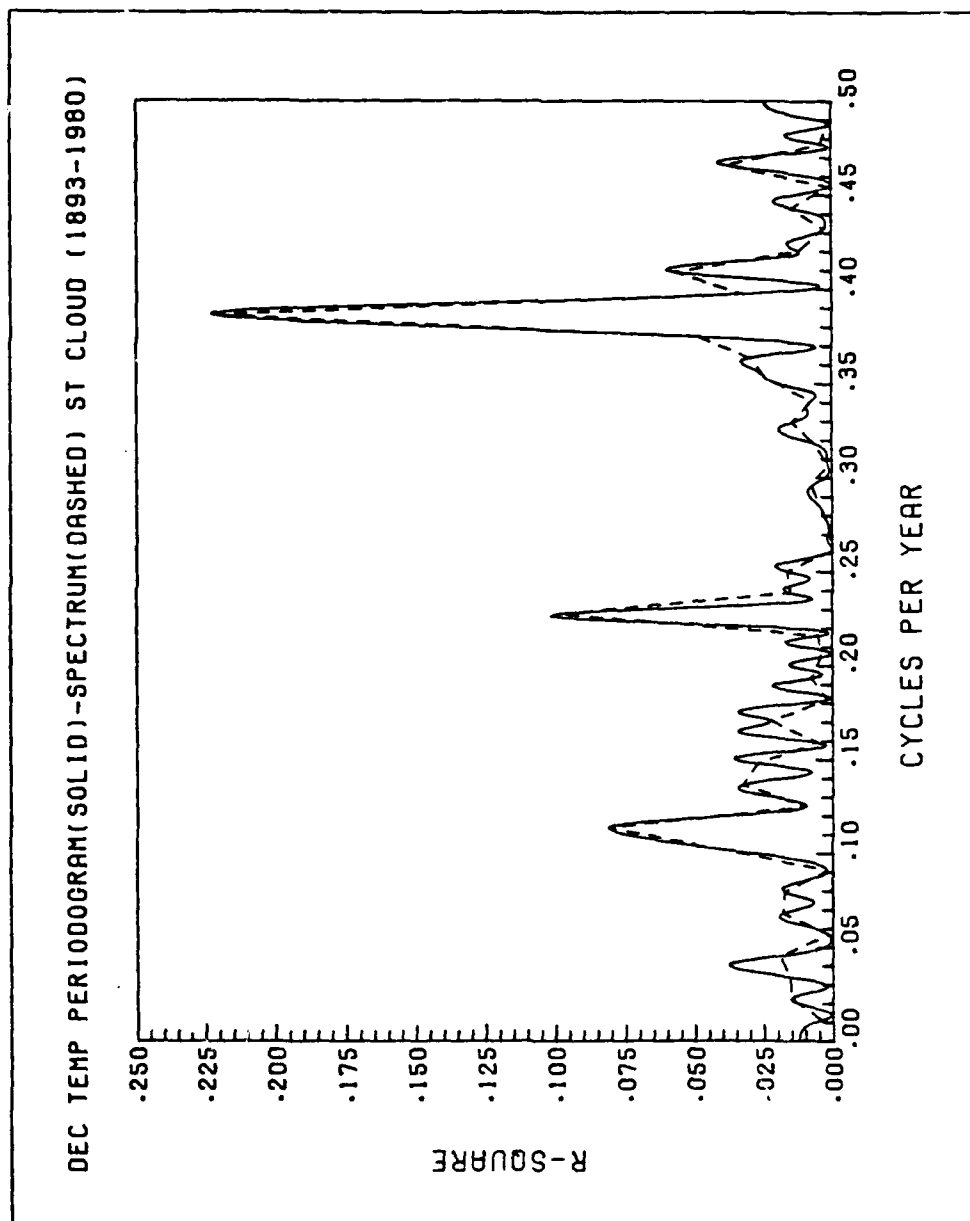


Figure 3. Periodogram (solid line) and variance spectrum (dashed line) of mean December temperatures (1893-1980) for St. Cloud, MN.

December temperature record at St. Cloud has three prominent peaks (Fig. 3). These three peaks explain approximately 40% of the temperature variation from one December to another. The variance peaks for frequencies of .3864 cycles/year, .2261 cycles/year, and .1136 cycles/year, explain 22%, 10%, and 8% of the variance, respectively.

The next step was to determine, as accurately as possible, the exact frequencies. Since the St. Cloud spectrum has 44 bands and the periodogram has 440 bands (see Appendix), the periodogram (solid line, Fig. 3) can be seen to increase the resolution of the spectrum (dashed line, Fig. 3). To further resolve each frequency, a nonlinear regression was performed on the St. Cloud December temperature data. This permitted a best fit to the temperature data using (1) but allowing the amplitude, phase angle, mean temperature, and most importantly the frequency, to vary.

$$(1) \quad T = \bar{T} + A \cos(2\pi f t + \phi)$$

An initial guess was required for each parameter and an iteration process converged on the final solution. The frequencies calculated from the variance spectrum were used as first guesses in the nonlinear regression technique. Each frequency was independently run and Table 1 lists the first guess and final solution for each of the three frequencies. The frequencies are listed in order of explained variance.

TABLE 1 St. Cloud Frequencies (cycles/year)

<u>First Guess</u>	<u>Lower bound</u>	<u>Final Solution</u>	<u>Upper Bound</u>
.3864	.3842	<u>.3868</u>	.3894
.2273	.2222	<u>.2263</u>	.2304
.1136	.1086	<u>.1132</u>	.1177

The bounds, in cycles/year, are at the 95% confidence limit. The three techniques, variance spectrum, periodogram, and nonlinear regression, progress toward a more exact frequency solution. The consistent results are shown in Table 2.

Table 2 St. Cloud Frequencies (cycles/year)

<u>Spectrum</u>	<u>Periodogram</u>	<u>Nonlinear Regression</u>
.3864	.3864	.3868
.2273	.2261	.2263
.1136	.1136	.1132

Because frequencies exhibited in the St. Cloud temperature record are of regional importance, as suggested by the results shown in Figure 2, these same frequencies should occur in other temperature records. This hypothesis was tested on temperature data from Minneapolis. First a spectrum was run on the December temperatures using an 88 year record, 1893-1980. The peaks in the spectrum were

then analyzed using the same nonlinear regression technique. The three frequencies explaining the most variance at Minneapolis were all within .0004 cycles/year of being identical to the same three frequencies at St. Cloud. The results support the assumption that whatever was forcing these systematic fluctuations (i.e. frequencies) in the temperature data must have occurred on a regional scale. The difference in the structure of the temperature spectra between St. Cloud and Minneapolis is almost negligible. Because there is more power in the St. Cloud spectrum, the frequencies .3868 cycles/year, .2263 cycles/year, and .1132 cycles/year, were used for additional experiments.

To further test the regional climatic signal, these three frequencies (.3868 cycles/year, .7736 cycles/year, and .1132 cycles/year) were regressed against December temperature records at 86 stations across the United States and Canada (see Appendix). Note that .7736 cycles/year was used instead of .2263 cycles/year with almost the exact result since .2263 cycles/year is within .0001 of being the alias frequency of .7736 cycles/year. The first harmonic of .3868 cycles/year is .7736 cycles/year. The resulting map, Figure 4, is a refinement of Figure 2 and shows the percentage of interannual variance of mean December temperatures explained by the combination of these three frequencies. The core of highest percentages extends from St. Cloud (41%) to Peoria (39.8%), with a large portion of the upper Midwest and south-central Canada lying inside the "greater than 20%" contour.

A time series is a convenient way to display a cyclic pattern

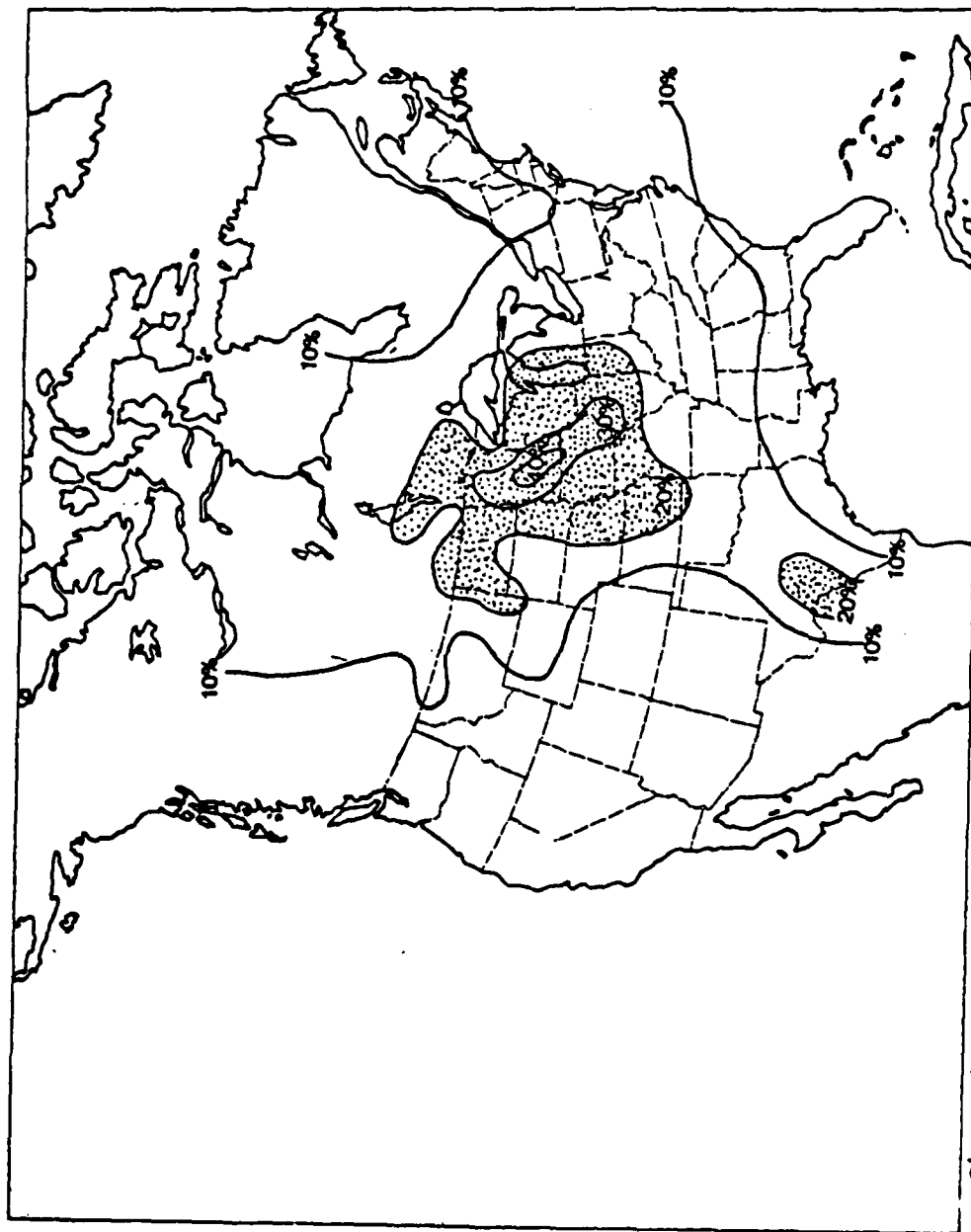


Figure 4. Variance of mean monthly December temperatures explained by .3868 cy/yr, .7736 cy/yr, and .1132 cy/yr. Obtained from regressions on each station's temperature record. Shaded area represents explained variance of 20% or more.

established by significant periodicities. Observations consistent or inconsistent with the regressed values can be well represented visually by using a time series. The chronological structure of a time series can also highlight important patterns. St. Cloud's December temperature record was regressed against .3868 cycles/year, .7736 cycles/year, and .1132 cycles/year. The solid line in Figure 5 is the regressed solution which can be used as a predictor, the dashed line is the observed mean December temperature. The time series created, Figure 5, provides good visual evidence that approximately 40% of the variation in December temperature data can be explained by the regressed curve. Indicated on the time series are the "cold" years (c) and the "warm" years (w) which best fit the regression. The "cold" years were arbitrarily chosen as years with temperatures more than .5 standard deviations below the mean. The "warm" years were chosen as years with temperatures more than .5 standard deviations above the mean. Best fit was defined as a difference between regressed and observed temperature of less than .5 standard deviations.

Many of these same warm and cold years were consistent with results from Minneapolis data using identical tests over the same period of record. The similarity between Minneapolis and St. Cloud temperature records at these three frequencies was expected since we were dealing with a regional phenomena as seen in Figure 4. Those years marked with "c" and "w" in Figure 5 will be used later to provide some insight relating the frequencies to synoptic pressure

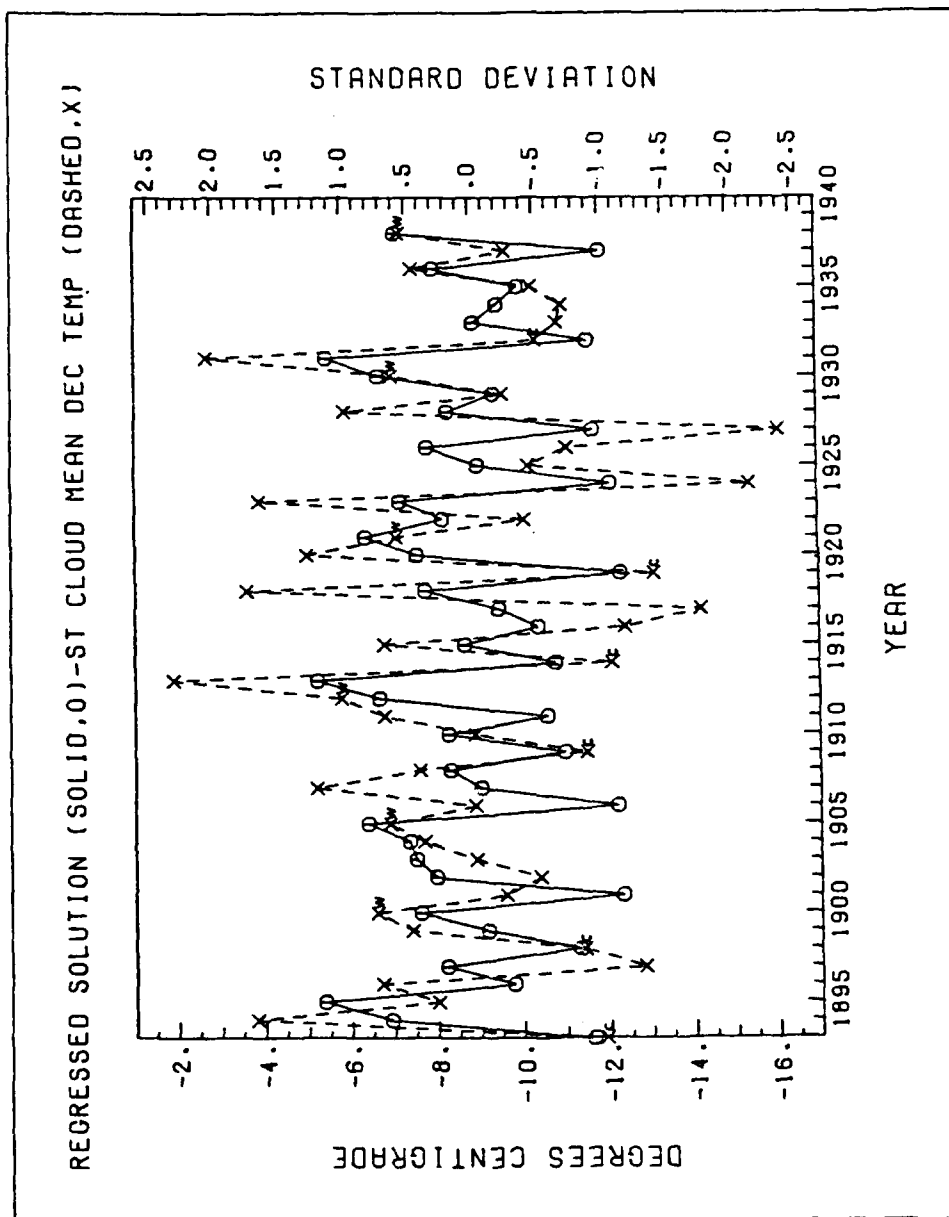


Figure 5. Time series (dashed line, X) of St. Cloud's mean December temperature (1893-1980). Regressed solution (solid line, O) using .3868 cy/yr, .7736 cy/yr, and .1132 cy/yr. "c" and "w" correspond to cold and warm years as defined in the text.

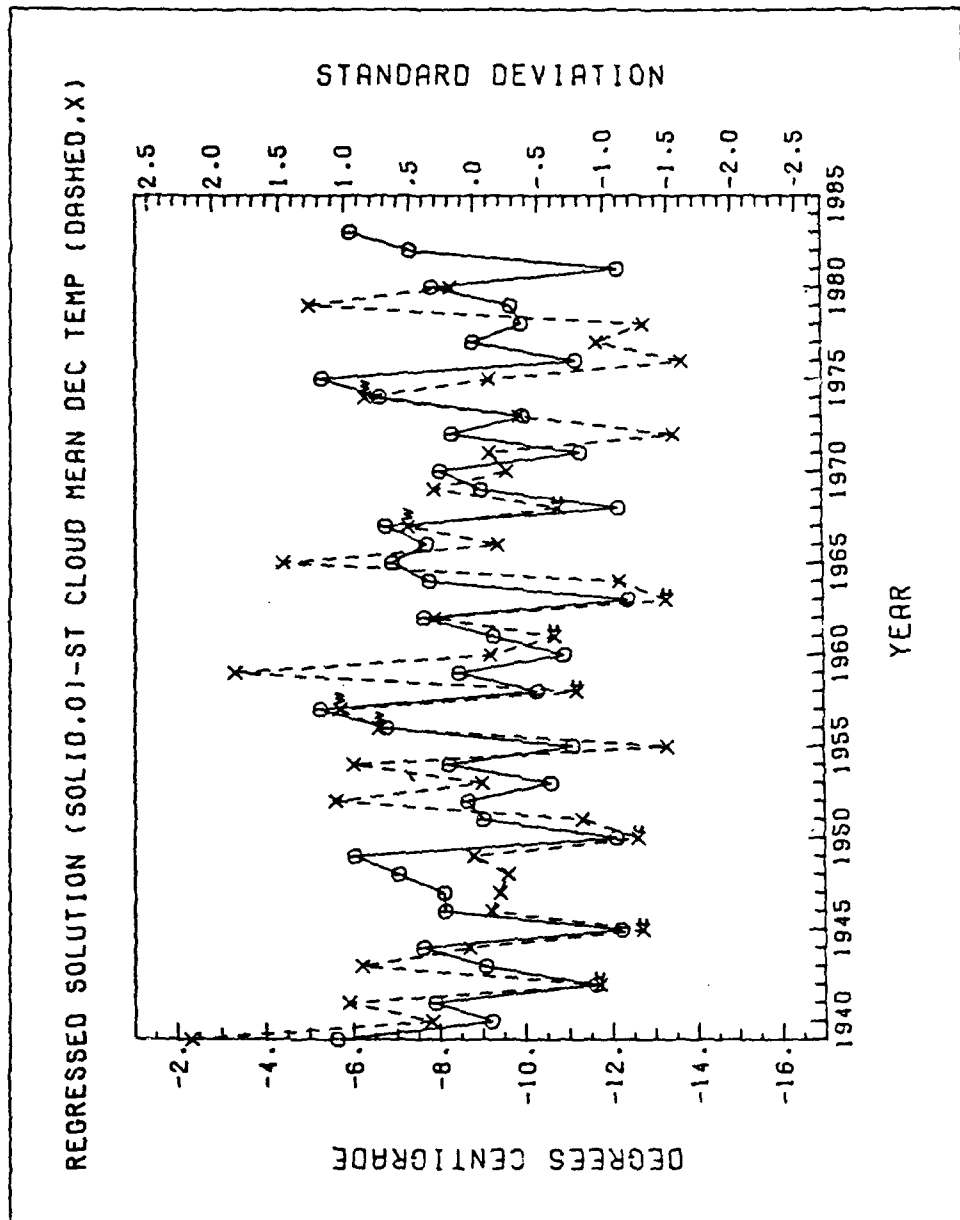


Figure 5 continued.

patterns.

Another way to represent the regression pattern of Figure 5 is to change the abscissa of the time series from years to degrees. This allows one cycle, 0° to 360° , to be examined. Each year is assigned a particular time phase in the cycle. For example, on an annual cycle ($f=1$ cycle/year), with January equal to 0° , June would be 180° or half way through the cycle. So the abscissa is really still a time scale even though it is in degrees. By applying a cycle concept to the time series, each year can be assigned a time phase, equal to $2\pi(ft)$. In the data, December 1899 was designated to be $t=0$ and the frequency was .3868 cycles/year. Each year ($t=1$ for 1900, $t=2$ for 1901, etc.) has a computed time phase based on the fundamental frequency, .3868 cycles/year, and is plotted at the appropriate time phase corresponding to the observed temperature for that year. For example, using .3868 cycles/year = f , and 51 years = t (December 1950), the time phase would be computed in the following manner:

- | | | | |
|----|-------------------------------------|---|-------------------------------------|
| 1) | (.3868 cycles/year)(51 years) | = | 19.7268 cycles |
| 2) | Subtract off 19 whole cycles | = | .7268 cycles |
| 3) | Multiply by 360° per cycle | = | <u>261.648$^{\circ}$</u> |

Therefore December 1950 would be plotted at 262° (Fig. 6). Each year is placed on the time phase axis based on the frequency used and when t equals zero. The vertical axis is simply the mean December temperatures ($^{\circ}\text{C}$) observed at St. Cloud.

The regression of a single frequency, .1132 cycles/year, has a sinusoidal shape with one cycle in 360° and December 1950 is plotted

at 278° in this cycle based on the frequency .1132 cycles/year (Fig. 7). More than one frequency can be shown on this type of graph if they are harmonics of each other. It is noted that .2264 cycles/year is the alias of .7736 cycles/year which is a harmonic of .3868 cycles/year. The first harmonic of .3868 cycles/year, .7736 cycles/year, would complete two cycles in exactly 360° of the fundamental. Thus, .3868 cycles/year and .7736 cycles/year cannot get out of phase with each other. They are said to be phase-locked and therefore can be plotted together. The effects of this harmonic on a simple sinusoidal pattern are seen in Figure 6. December 1950 is plotted at 262° in this .3868, .7736 cycle.

Figures 6 and 7, with the "cold" and "warm" years underlined, present the same information shown in Figure 5. The cyclic pattern displayed in the time series is more obvious in Figures 6 and 7. The frequencies in Figure 6 show a stronger amplitude and explain more of the temperature variance than the frequency in Figure 7. As an example of the similarity between Figures 5, 6 and 7 we can again look at December 1950. Figure 6 shows a regressed anomaly of 3.32°C below the mean (-8.88°C) at 262° . Figure 7 shows a $.07^{\circ}\text{C}$ anomaly above the mean at 278° . Thus, for December 1950 the regressed value using all three frequencies is 3.25°C (Figs. 6 and 7) below the mean. This corresponds to the same regressed value of -12.13°C shown in Figure 5. This is the coldest part of the cycle. The time phase graphs break the frequencies in a time series down into their components. The anomalies calculated from different frequencies

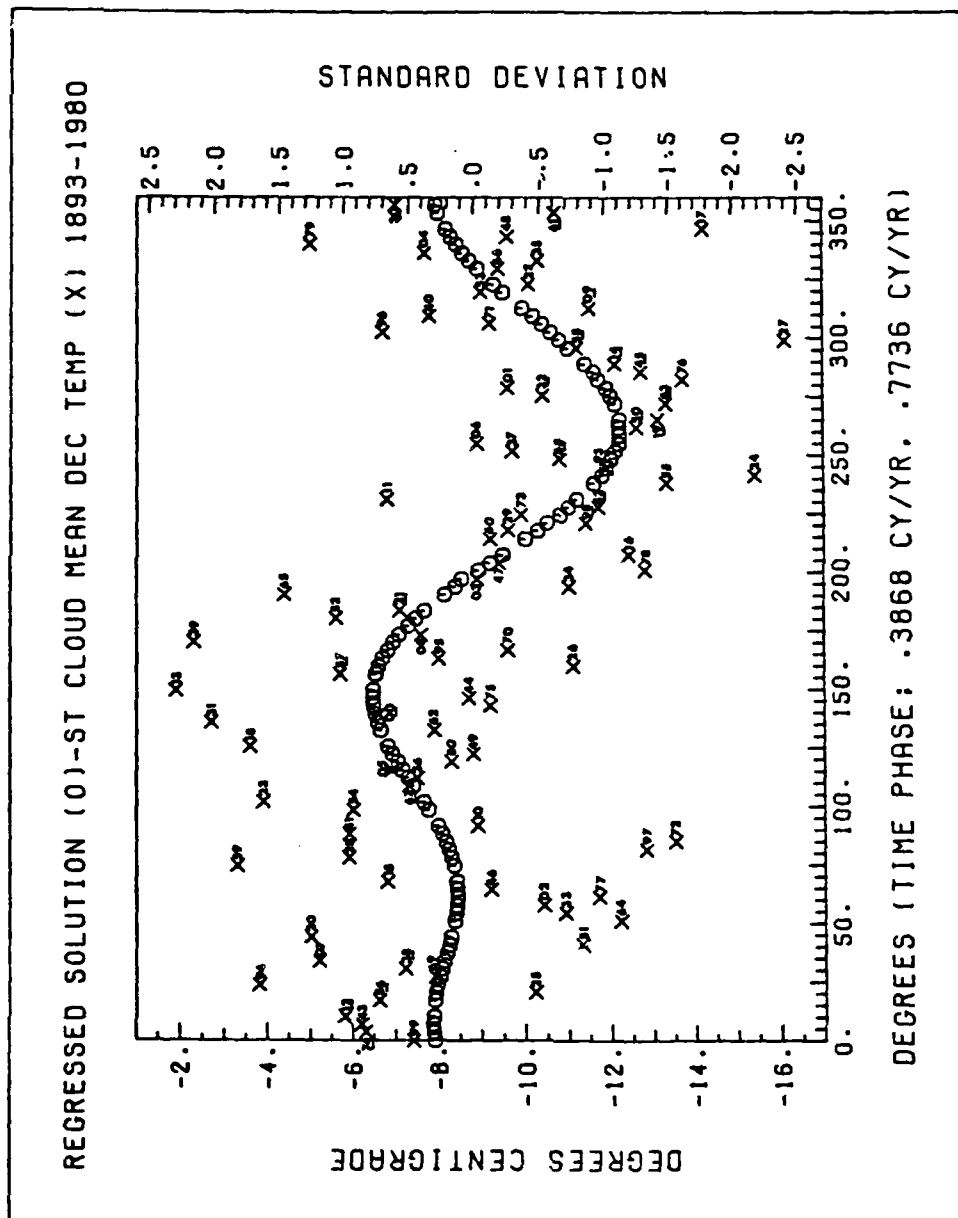


Figure 6. Mean December temperatures (1893-1980) for St. Cloud with the year indicated next to the "X". Warm and cold years as defined in the text are underlined. "O" indicates the regressed solution using .3868 cy/yr and .7736 cy/yr.

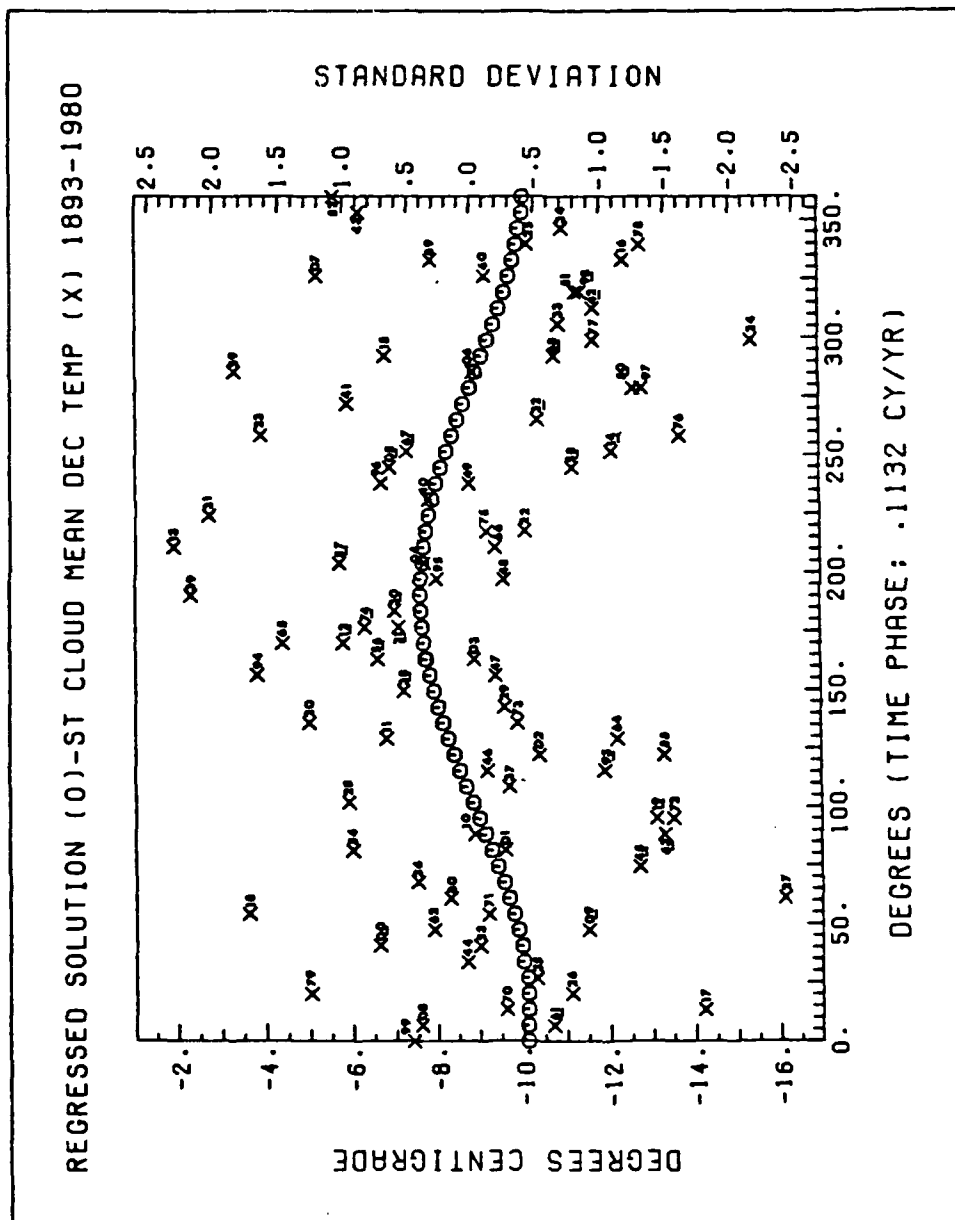


Figure 7. As in Fig. 6 except regressed solution ("O") using .1132 cy/yr.

can be added by using the same time (t) but can not be added by using the same phase. For example, the regressed anomaly for 1950 (time) at 262° (phase) using .3868 cycles/year can be added to the regressed anomaly for 1950 (time) at 278° (phase) using .1132 cycles/year, but the regressed values at 262° (phase) using .3868 cycles/year can not be added to the regressed values at 262° (phase) using .1132 cycles/year.

The ability to compute the regressed value and time phase for any year past or future and to know where that year is in the cycle is a useful feature. To use these frequencies with confidence in the future the frequencies must exhibit stability over various time intervals in the past. Overlapping incremental regressions were run using a 22 year record length. Each successive regression was advanced by four years. Amplitudes of .3868 cycles/year and .7736 cycles/year were calculated. The results (Fig. 8) indicate that when the fundamental's amplitude was large, the harmonic's amplitude was small and vice versa. Combining both frequencies therefore provides optimal stability. Explained variance (see Appendix), with the two frequencies combined, ranged from 26% to 65%. The variation in the amplitude of these frequencies seems to be occurring in a cyclic manner. Changes in amplitude may also imply that the frequencies shift slightly with time. Even though the amplitudes of these frequencies vary in time, they are stable enough to be effective predictors. Having shown the reliability in time, the position in the cycle of December 1983, for example, can be computed. Using .3868

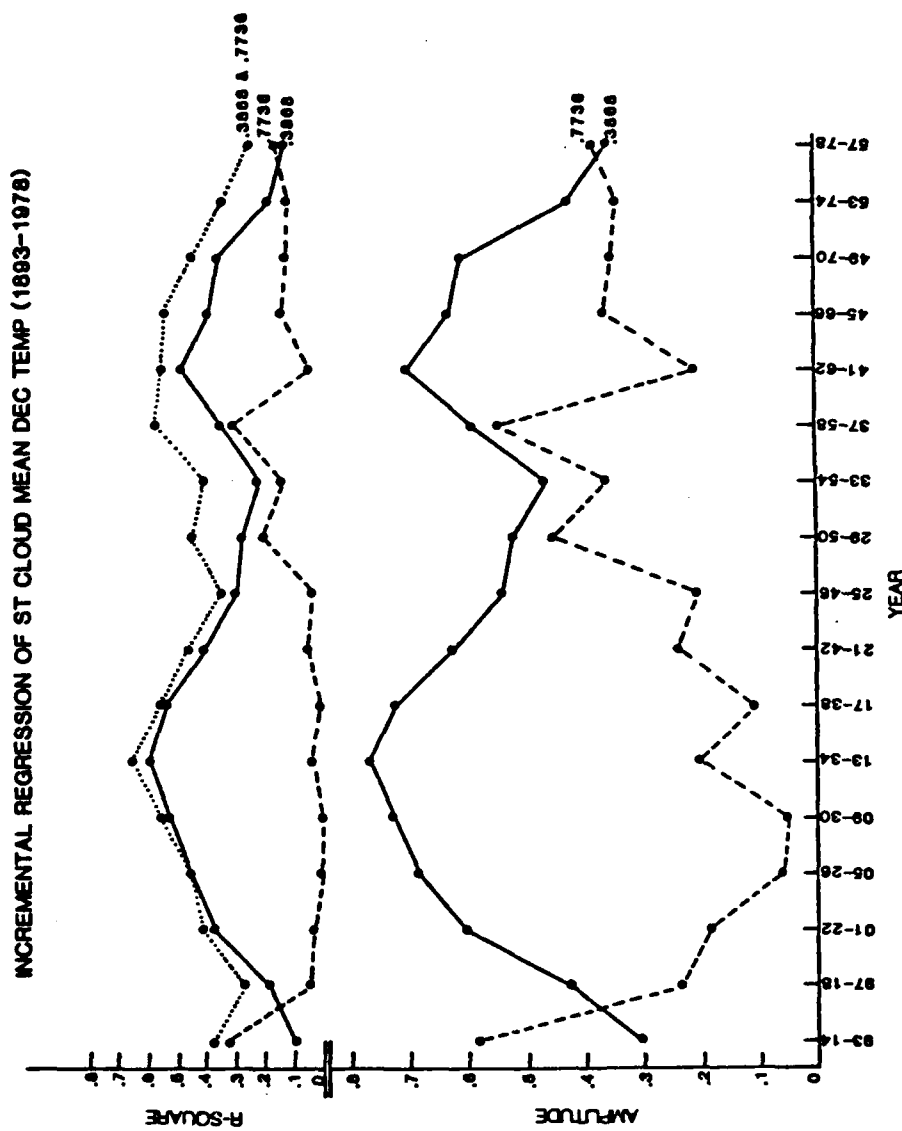


Figure 8. 17 regressions with four year increments using 22 year record lengths. (Top) Explained variance for .3868 cy/yr (solid), .7736 cy/yr (dashed), and .3868 cy/yr combined with .7736 cy/yr (dotted). (Bottom) Amplitude for .3868 cy/yr (solid) and .7736 cy/yr (dashed).

cycles/year and its harmonic, December 1983 has a time phase of 177° . In Figure 6 this is in the warm part of the cycle, 1.6°C above the mean. December 1983 also lies in the warm part of the cycle for .1132 cycles/year. Figure 7 shows that December 1983 would be at 183° in the .1132 cycle with a regressed value 1.3°C above the mean. The total anomaly, 2.9°C , uses all three frequencies and indicates a warmer than normal December for 1983. The result for December 1983 is extrapolated out in the time series, Figure 5. This sample forecast is most applicable at St. Cloud where the regression using the three strong frequencies seen in Figure 4 explains approximately 40% of the variance in December temperatures. The results of this temperature analysis indicate that three frequencies near .387 cycles/year, .226 cycles/year, and .113 cycles/year dominate the December temperature time series in a large area of the upper Midwest. These frequencies, used in constructing a time series and making predictions, will be utilized more in the following sections.

PRESSURE ANALYSIS

Because the temperature analysis indicates a regional effect, it is useful to examine the climatics of the December flow pattern in the upper Midwest. December is often a transition month, from a mild, Pacific-dominated flow pattern (zonal), to a cold, Arctic-dominated flow pattern (meridional). The shift from a mild, autumn flow pattern to a cold, winter flow pattern is associated with the transition of the Aleutian low from the Gulf of Alaska to the Aleutians. In a "natural calendar" sense between the 8th and 28th of December the normal sea level pressure charts show the Aleutian low moving from the autumn to winter position. Therefore, December represents a period during which the transition to a winter pattern occurs (Bryson and Lahey, 1958). The onset and reoccurrence of cold outbreaks associated with Canadian highs, determines if December will be a colder than normal month for the upper Midwest. Recent evidence suggests a similar "natural calendar" event occurs in June, with a shift from cool spring patterns to hot summer patterns (Bryson, 1982, personal communication).

The effects of small changes in the mean December pressure pattern can be seen in Figure 9. This mean surface December pressure pattern was obtained from 80 years of gridded pressure data from 1899 to 1978. The main features of this map include extensions of the Icelandic low in northeast Canada, the Aleutian low in western Canada and the Gulf of Alaska, the Canadian and Great Basin high and the high

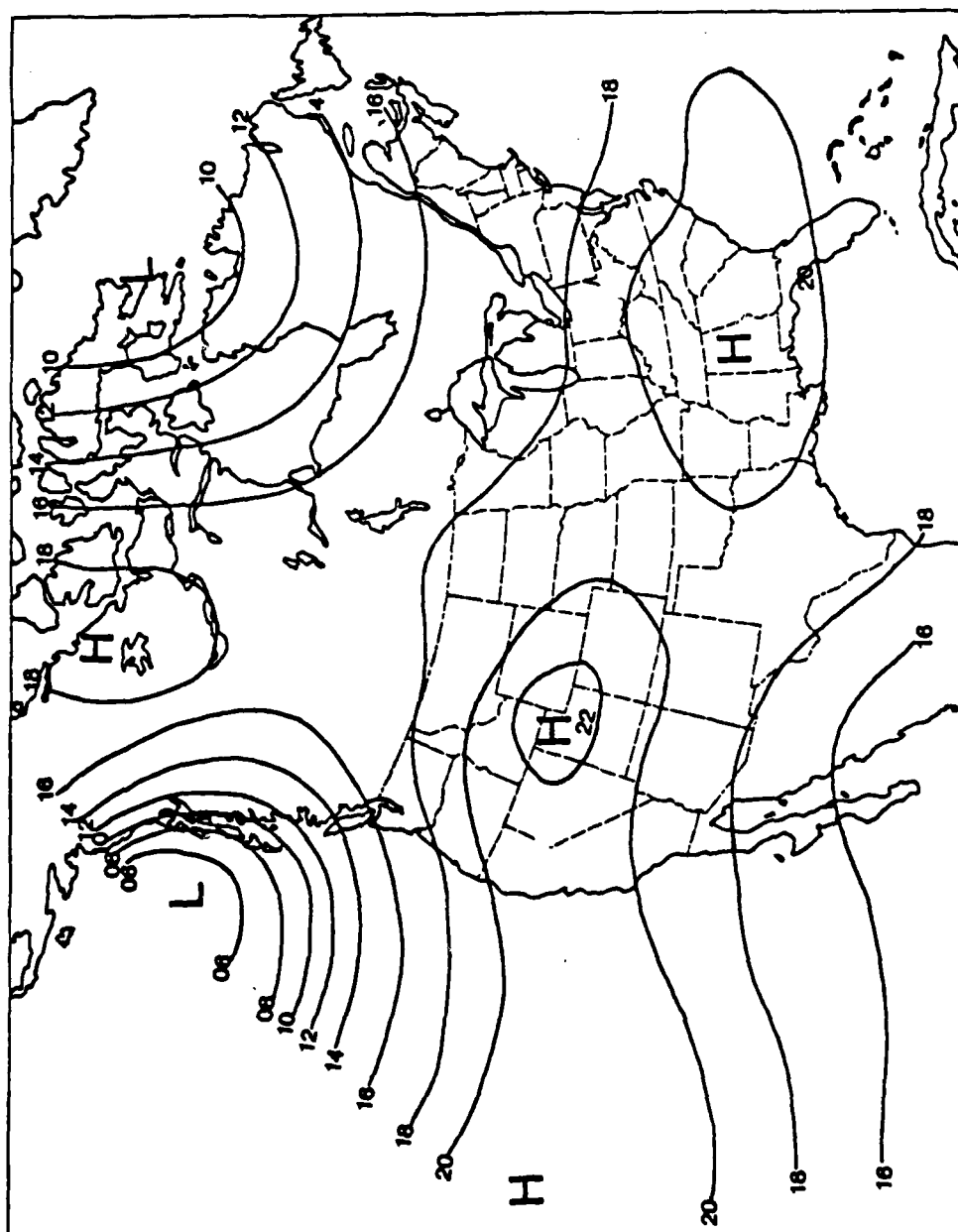


Figure 9. Mean December (1899-1978) sea level pressure pattern (units in millibars minus 1000).

over the southeast United States. What areas will be most sensitive to slight changes in the intensity or pattern of these prominent pressure features? Certainly an area under or near a high or low pressure will not experience a significant change in weather if the system is only slightly altered. Large temperature changes can occur with only a small synoptic change in an area that is sensitive to shifting wind patterns from one December to the next. A region of weak mean pressure gradients would show a temperature sensitivity to slight pressure pattern changes. With slight pressure variations one December will look much like the next where the pressure gradients and pressure patterns are strong and the wind pattern is well established. But one must look between the systems or near the boundaries of a system. South-central Canada, the upper Midwest (north-central United States) and west-central Texas, represent sensitive areas which may be more responsive to the domination of a particular pressure system. If the Icelandic low is stronger or slightly displaced southward in a particular December, then there will be more northerly winds than normal in the upper Midwest, resulting in a colder December. Likewise, if the Aleutian low is more intense with a trough extending inland over western Canada, then a more zonal flow is established and the upper Midwest experiences a mild December. These examples suggest that there would be more interannual variability of the wind directions in these sensitive areas. A subtle change of flow pattern can result in a large temperature response in certain sensitive areas. Slight variations in the positions of the

principal action centers might be quite insignificant for the large-scale circulation, but have great effects on the temperature behavior of a specific area (Wahl, 1952).

Figure 4 and Figure 9 can be compared to illustrate the pattern of explained variance (greater than 20%) of temperature due to the frequencies .3868 cycles/year, .7736 cycles/year, .1132 cycles/year, and the mean December pressure pattern. The shaded area in Figure 4 lies between the main pressure systems and their associated pressure gradients dominant in Figure 9. Figure 4 appears to indicate a sensitive area which is on or close to strong mean temperature gradients.

Streamlines drawn from data in the 1930's (Bryson, 1966) show that the source of air over the north-central United States in December, on the average, is primarily Pacific air (Fig. 10). The boundaries between Pacific air and Arctic air and between Pacific air and air from the south are not far from the upper Midwest. These boundaries are also very transitory. Because the 1930's were a warm period, the Arctic boundary may have shifted northward. A suggested streamline analysis (Fig. 11) drawn from the mean pressure map (Fig. 9) shows a broad confluence zone covering the region of air mass boundaries seen in Figure 10. Whatever air mass dominates a region for a particular month will determine the weather for that month. Numerous Arctic air masses will cause cold and dry conditions to prevail. Pacific air masses or air masses from the south will generate a mild pattern for the month. The purpose of the pressure and streamline analysis

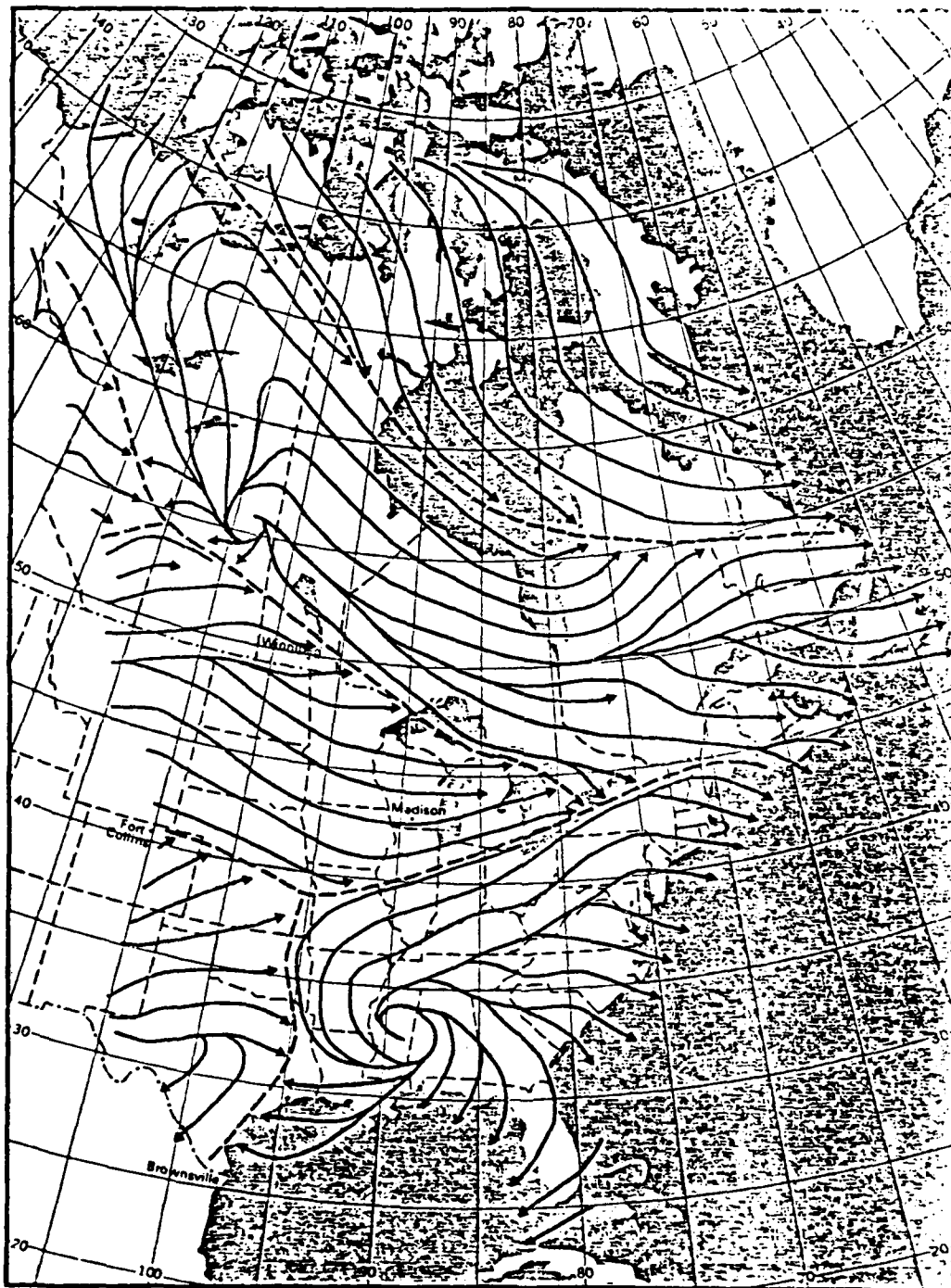


Figure 10. Streamlines of the surface resultant wind in December.

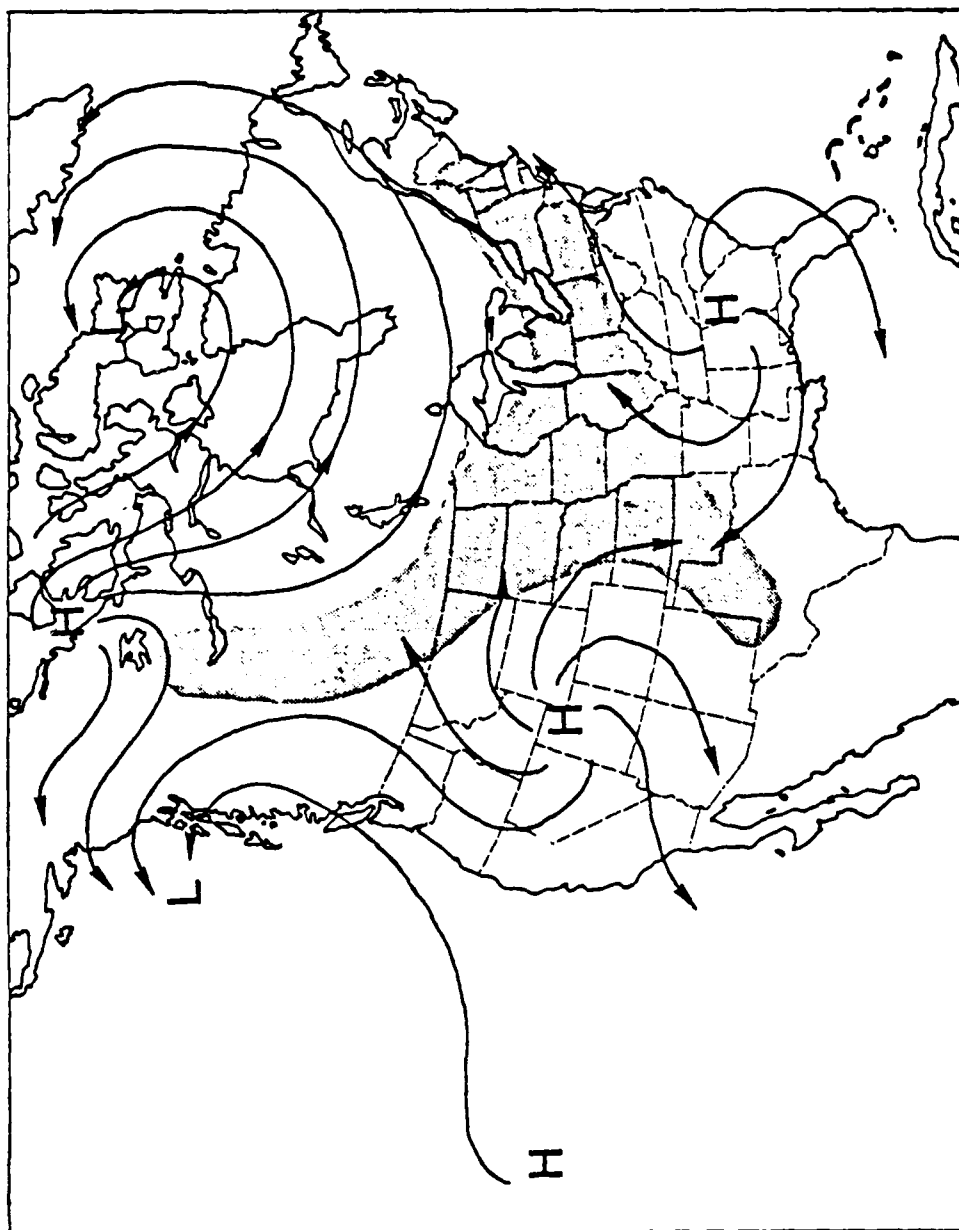


Figure 11. Streamline analysis estimated from mean December pressure map (Fig. 9). Shaded area represents a possible mean confluence zone.

(Figures 9, 10 and 11) is to direct the investigation to a region where small changes in surface pressure patterns can force large changes in observed temperature patterns in areas along or in the vicinity of these air mass boundaries, or confluences. The shaded area in Figure 11 represents a confluence zone. Station temperature records in and near this confluence zone may provide data which are sensitive to the movement of the mean front because these regions have strong mean temperature gradients. The mean monthly confluence zones do not progress regularly north and south, but stay in one position for several months (a meteorological season) and then move abruptly to a new seasonal position (Bryson, 1966). When in December this abrupt change occurs will determine the mean temperature pattern for the month. Because the temperature pattern exhibits a periodicity, the "forcing" pressure pattern might also. Is the type of air mass which dominates a region forced into that region in a cyclic manner?

The hypothesis to be tested is that air masses and pressure patterns are being altered or modulated by the frequencies (.3868 cycles/year, .7736 cycles/year, and .1132 cycles/year) observed in the temperature records in the north-central United States, and synoptically these frequencies explain the "warm" versus the "cold" Decembers in the upper Midwest. Frequencies similar to those in the temperature data are found in the pressure data in the Northwest Territories of Canada where the Yukon high dominates. These frequencies in pressure data will be examined later. Since the pressure patterns are the immediate synoptic cause of temperature

patterns, the frequencies discovered in the temperature data at St. Cloud were used in a regression with pressure data.

Mean monthly December sea level pressure data were used for a period from 1899 through 1978. Data were obtained at latitude and longitude grid intersections using a diamond pattern to get the best resolution. Grid points were used at all even latitude and longitude intersections (e.g. 30°N , 70°W) and all odd latitude and longitude intersections (e.g. 35°N , 75°W). Pressure data from 20°N to 70°N latitude and 70°W to 140°W longitude were considered adequate for synoptically explaining temperature variations in the north-central United States. The same linear regression procedure previously applied to temperature data, is also utilized for pressure analysis (see Appendix). Using the formula analogous to (1), regressions on the pressure data at each grid intersection were calculated.

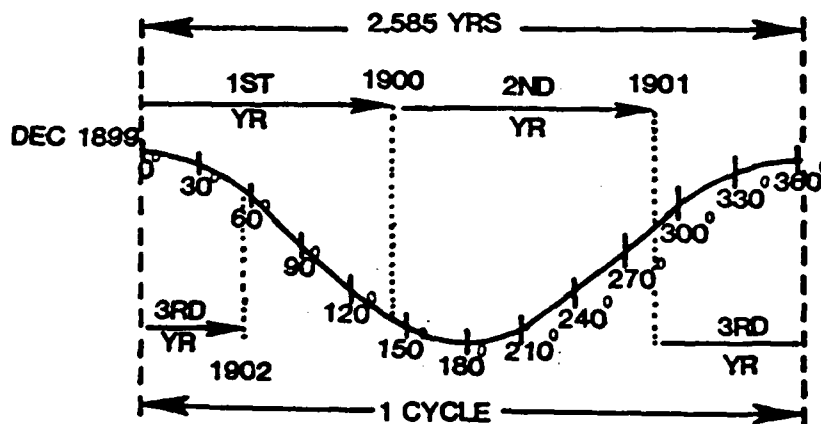
$$(2) \quad P = \bar{P} + A \cos(2\pi ft + \phi)$$

With the mean pressure removed, and the amplitude and phase angle determined for a given frequency, the pressure anomaly can be computed for a particular grid point. This procedure is repeated for each grid point until a map of pressure anomalies is obtained. The parameter t in (2) provides the flexibility of examining different parts of the cycle of frequency f . If we let $t=0$ in December 1899 and let $f=.3868$ cycles/year, $2\pi(ft)=139.25^{\circ}$ in December 1900 when $t=1$. Likewise each year can be assigned a value in degrees. A pressure anomaly could be determined at each grid point based on the frequency used and

the specific year. By analyzing all the gridded data a pressure pattern anomaly map can be drawn for a given year based on the frequency .3868 cycles/year. To slightly alter this line of thought, assume we only want to look at particular time phases in the cycle, say 0° , 30° , 60° , and so forth to 330° . Now we must set $2\pi(ft) = 0^\circ$, 30° , 60° or 90° and so on, so the pressure pattern reflects the progression through the cycle (0° to 360°).

For example:	$2\pi ft = 30^\circ$	$2\pi ft = 180^\circ$
($f = .3868$ cy/yr.	$t = .215$ yrs.	$t = 1.293$ yrs.
or 2.585 yrs/cy)	$t = 2.80$ yrs.	$t = 3.878$ yrs.
	$t = 5.38$ yrs.	$t = 6.463$ yrs.
	$t = 7.97$ yrs., etc.	$t = 9.048$ yrs., etc.

These calculations at specific time phases allow one to look at certain years and see where they are in the cycle. When $t = 7.97$ years, 1907 should be very close to 30° in the cycle and when $t = 9.048$ years, 1908 should be close to 180° in the cycle. An example of the cosine function using .3868 cycles/year is shown below.



The third year, 1902, shows up in the cycle at 57.7° . Thus all 80 years (1899-1978) are represented somewhere between 0° and 360° . Instead of looking at 80 individual pressure maps corresponding to each year and placing them in order with respect to the cycle, the analysis is simplified by looking at twelve pressure maps (0° through 360° , every 30°) and noting how the anomalous pressure pattern changes through the cycle.

The temperature spectrum at St. Cloud (Fig. 3) shows another peak in power near .2264 cycles/year. The related pressure pattern must include .2264 cycles/year and .3868 cycles/year. In (3), .7736 cycles/year was used as the first harmonic of .3868 cycles/year, since .7736 cycles/year aliases at .2264 cycles/year. This harmonic pattern was seen in the temperature regression curve in Figure 6.

$$(3) \quad P = A \cos[2\pi(.3868)t + \phi] + A_h \cos[2\pi(.7736)t + \phi_h]$$

Combining these frequencies, (3) was solved for each grid point using linear regression techniques. The resulting maps, Figures 12a to 12l, were drawn by applying this procedure to each 30° phase of the cycle. These maps show pressure anomalies in millibars corresponding to a given time phase in the cycle. Since the maps represent anomalous patterns, one can infer that each map displays what is different about that part of the cycle from a normal or mean pattern (Fig. 9). By looking at a particular time phase in the cycle one can see to what degree the flow behaves anomalously. A comparison can be made by looking at the cluster of "warm" Decembers near 150° and "cold" Decembers near 270° in the cycle (Fig. 6). The corresponding

pressure maps (Figs. 12f and 12j respectively) appear to explain synoptically why warm and cold Decembers occurred in the upper Midwest. At 150° in the cycle (Fig. 12f) there is more Pacific flow than normal with mild westerly and southwesterly winds. This synoptic pattern causes a warmer than normal month. At 270° in the cycle (Fig. 12j) anomalous northerly flow dominates the upper Midwest, allowing colder than normal temperatures to infiltrate this area. These pressure anomaly maps are a tool to synoptically explain some of the temperature observations at various phases seen in Figure 6.

Another refinement to this analysis is to include the third important frequency, .1132 cycles/year. This frequency must be considered independent of the other two, since .1132 cycles/year is not a harmonic of .3868 cycles/year and therefore not phase locked. In addition, a larger response would be observed by combining .3868 cycles/year and .2264 cycles/year rather than .1132 cycles/year and .2264 cycles/year. Therefore, the pressure pattern anomaly maps using .1132 cycles/year were analyzed separately (maps not shown) following the same procedure used to generate the previous pressure anomaly maps (Figs. 12a to 12i). The magnitude of the .1132 anomalies is smaller since the amplitude of .1132 cycles/year is smaller. Thus the effect of .1132 cycles/year on the overall pressure pattern is also smaller. The pressure maps based on the frequencies .3868 cycles/year, .2264 cycles/year, and .1132 cycles/year can be used in the proper combination to represent a pressure anomaly pattern for a given year. A qualitative case study approach can be used to synoptically explain

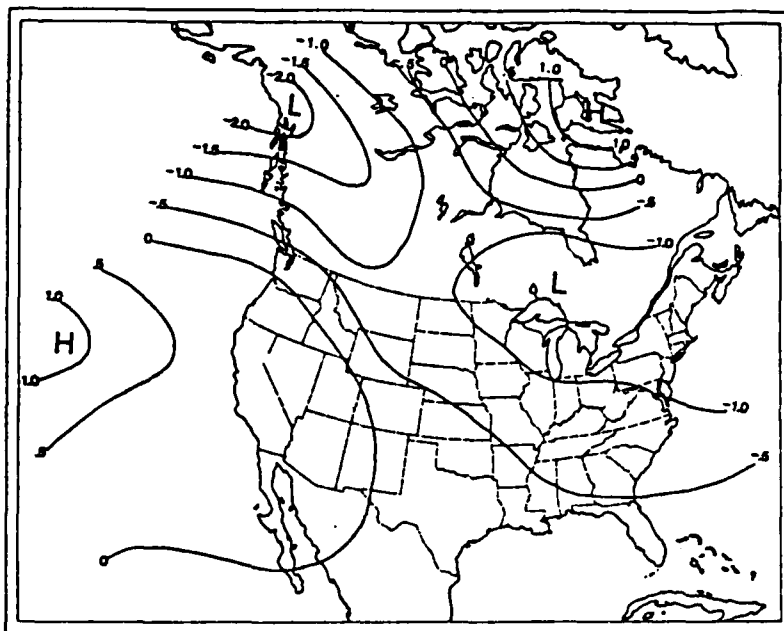


Figure 12a. Anomalies (in millibars) from the mean using gridded pressure data (1899-1978) regressed against .3868 cy/yr and .7736 cy/yr. Time phase is at 0° or 360° in the cycle.

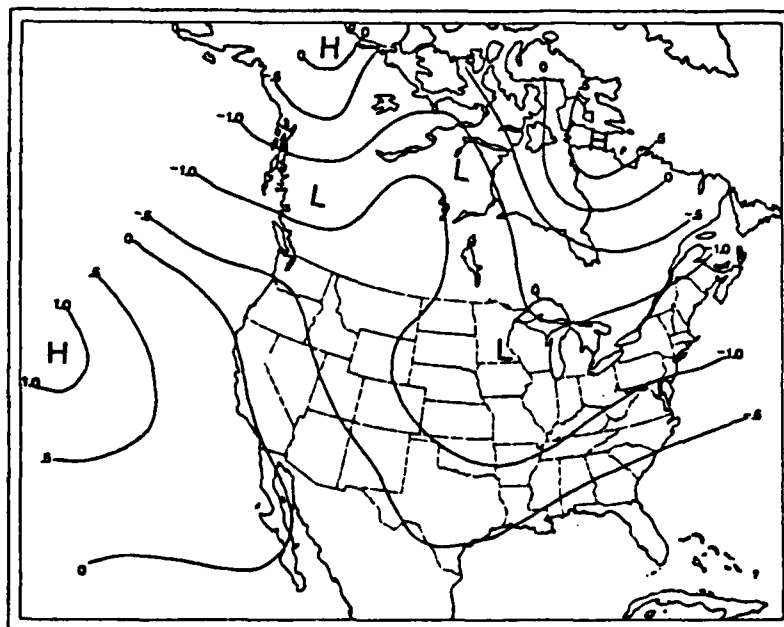


Figure 12b. As in Fig. 12a except time phase is at 30° in the cycle.

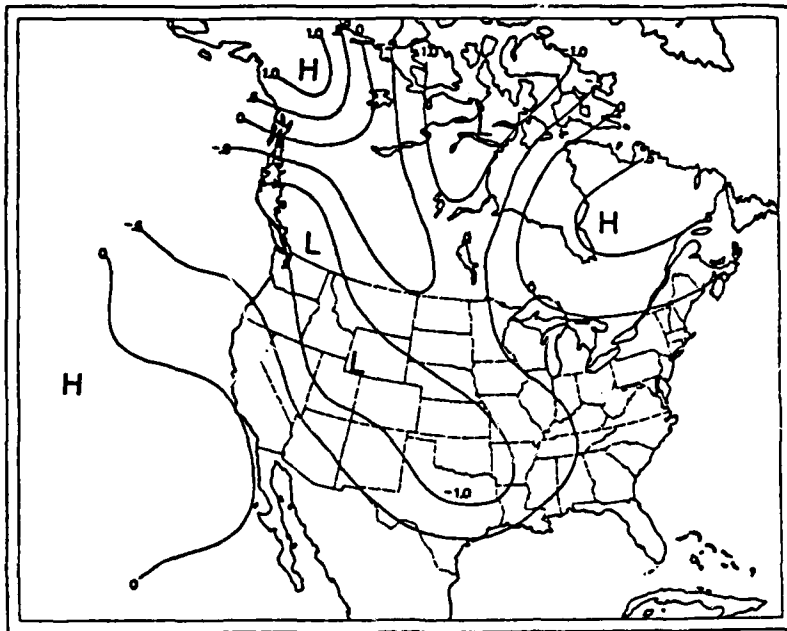


Figure 12c. As in Fig. 12a except time phase is at 60° in the cycle.

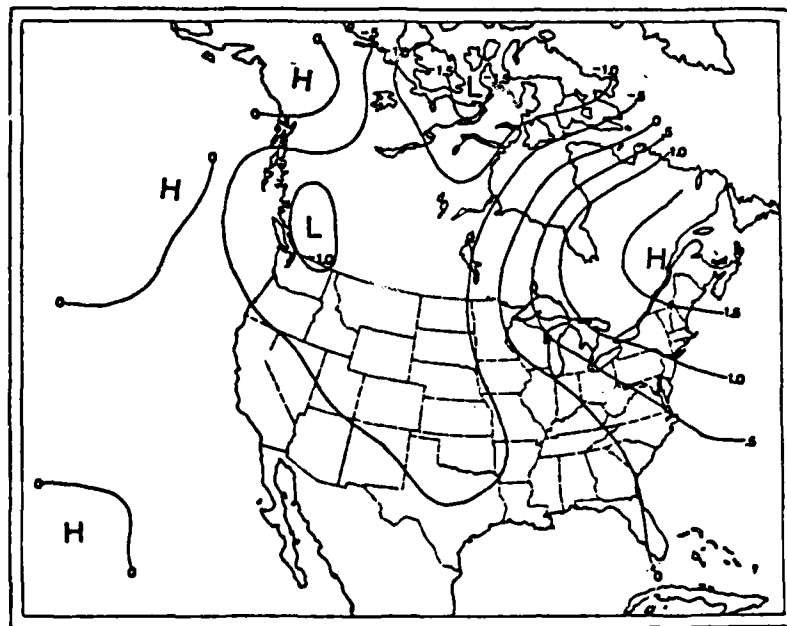


Figure 12d. As in Fig. 12a except time phase is at 90° in the cycle.

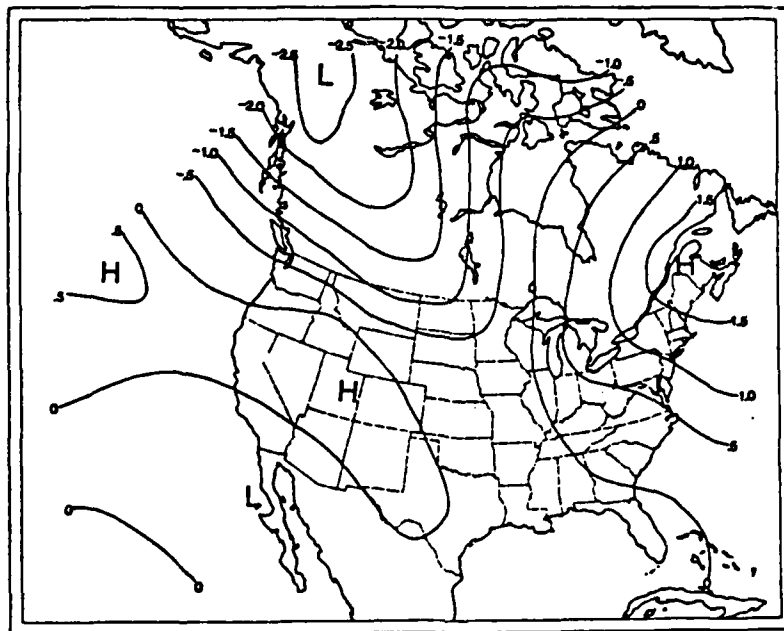


Figure 12e. As in Fig. 12a except time phase is at 120° in the cycle.

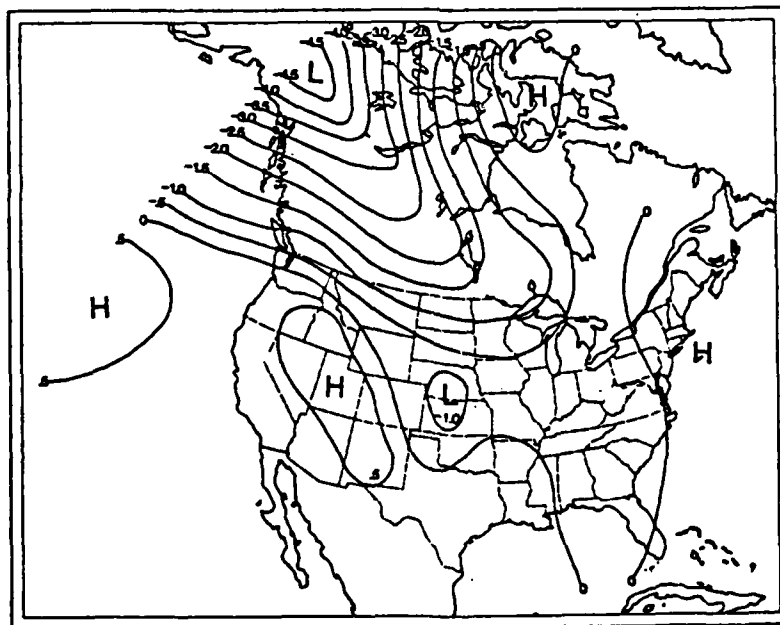


Figure 12f. As in Fig. 12a except time phase is at 150° in the cycle.

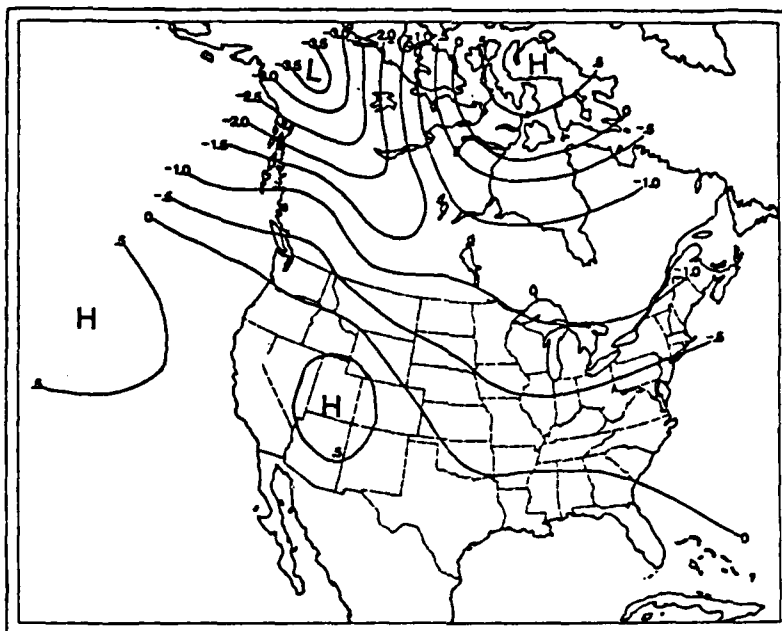


Figure 12g. As in Fig. 12a except time phase is at 180° in the cycle.

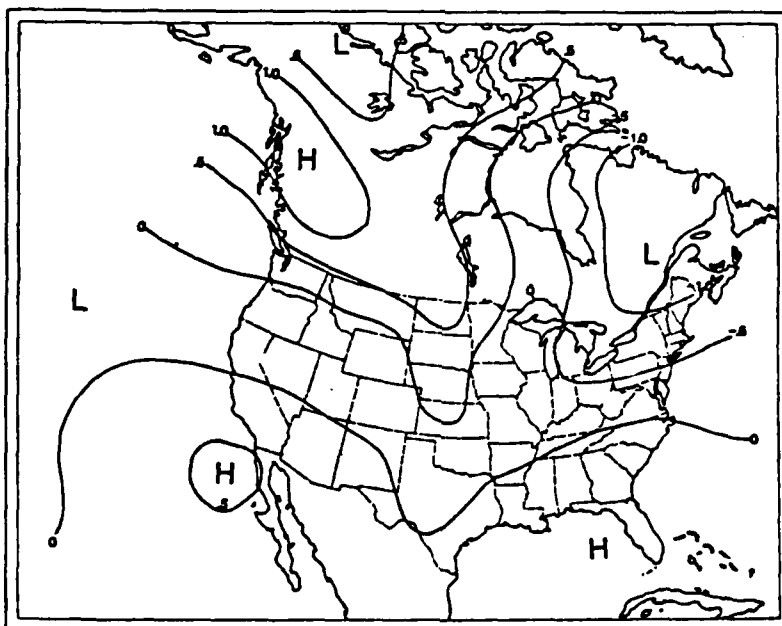


Figure 12h. As in Fig. 12a except time phase is at 210° in the cycle.

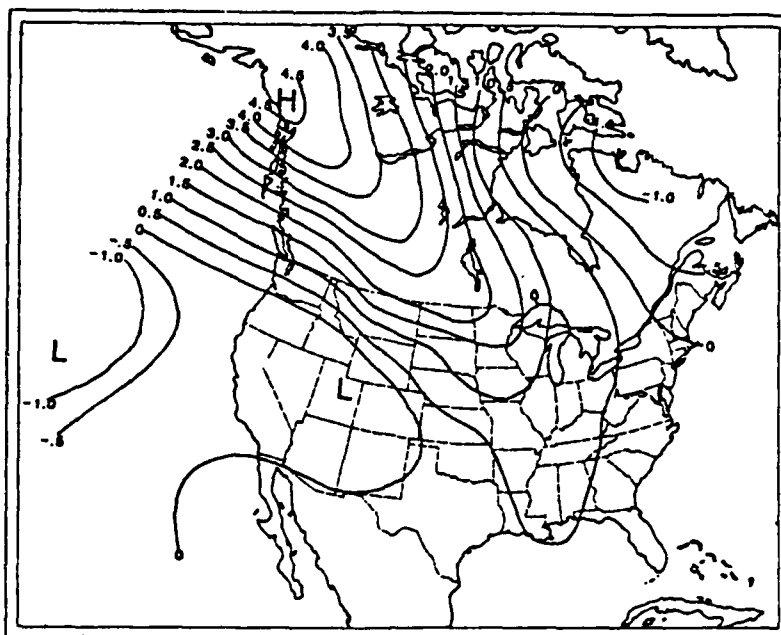


Figure 12i. As in Fig. 12a except time phase is at 240° in the cycle.

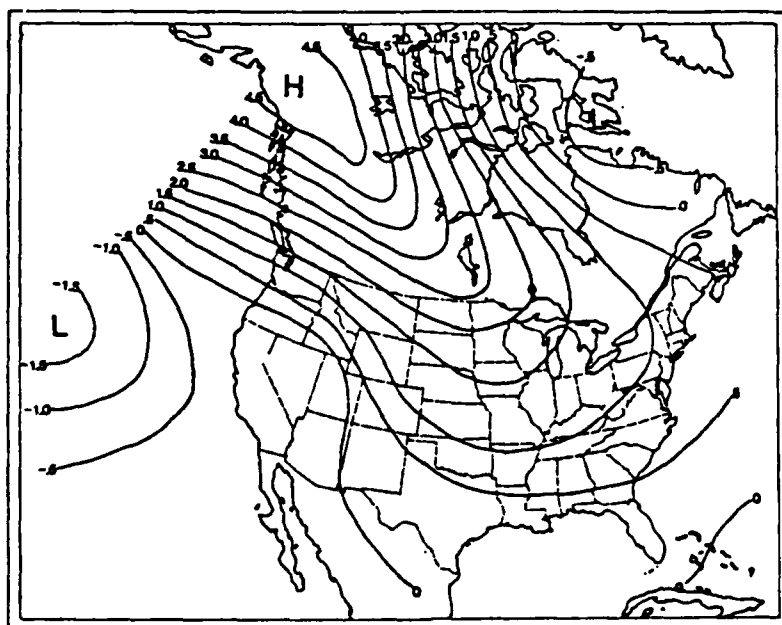


Figure 12j. As in Fig. 12a except time phase is at 270° in the cycle.

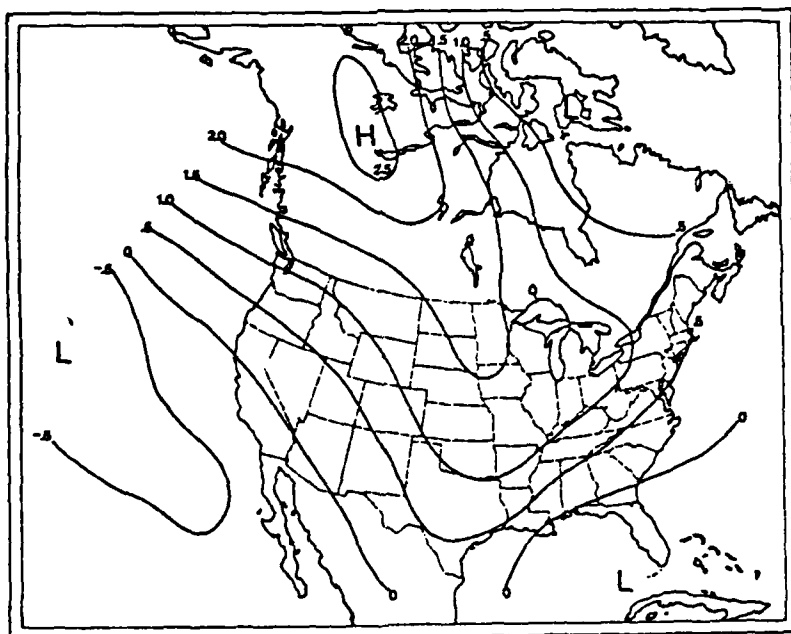


Figure 12k. As in Fig. 12a except time phase is at 300° in the cycle.

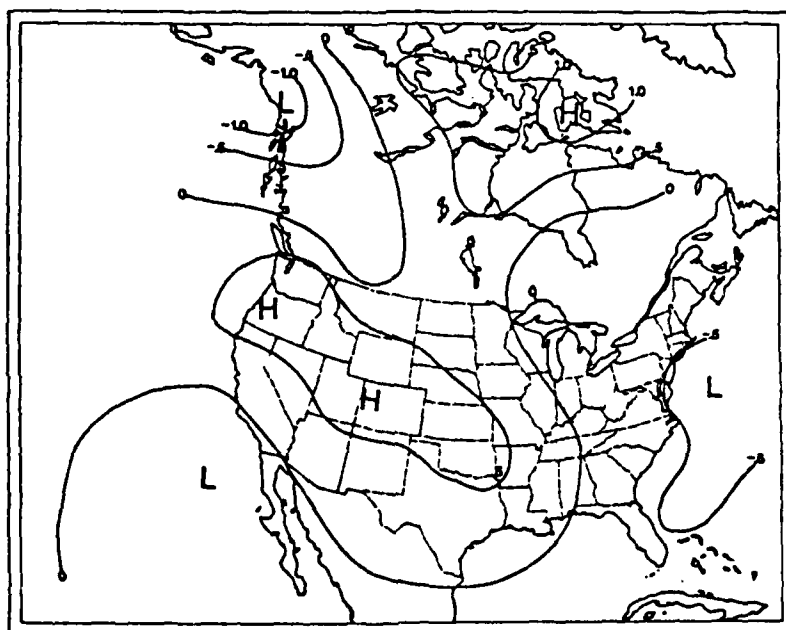


Figure 12l. As in Fig. 12a except time phase is at 330° in the cycle.

the "cold" and "warm" Decembers.

Two examples will be given to help clarify the procedure. December 1950 was one of the "cold" years referenced earlier that applied to both St. Cloud and Minneapolis. By looking at Figure 6, 1950 is seen to have been a year which approximately fits the regression, and was a cold year near the minimum regressed value in the cycle. As a first test, can the pressure maps explain this cold year? Using the formula for time phase, $2\pi(ft)$, where $f=.3868$ cycles/year and $t=51$ years (1899 to 1950), the time phase is 261.6° which is where 1950 is plotted on Figure 6. An examination of Figure 12j helps to explain what happened synoptically based on the fundamental frequency .3868 cycles/year and its harmonic. This pressure anomaly map shows the pattern at 270° in the cycle. This approximates the time phase of 262° calculated for December 1950. December 1950 at St. Cloud, and in most of the north-central United States, should have had more northerly and stronger flow than a normal December (anomalous pattern) based on the frequencies .3868 cycles/year and .7736 cycles/year. The mean pressure map drawn from the observed gridded pressure data for December 1950 (Fig. 13) shows a synoptic pattern indicating a mean flow from the north over the upper Midwest.

The pressure pattern also has some interannual variation with a frequency of .1132 cycles/year. This frequency (.1132 cycles/year) is not as significant because it has an amplitude about half as large as .3868 cycles/year and its harmonic (compare Fig. 7 versus Fig. 6).

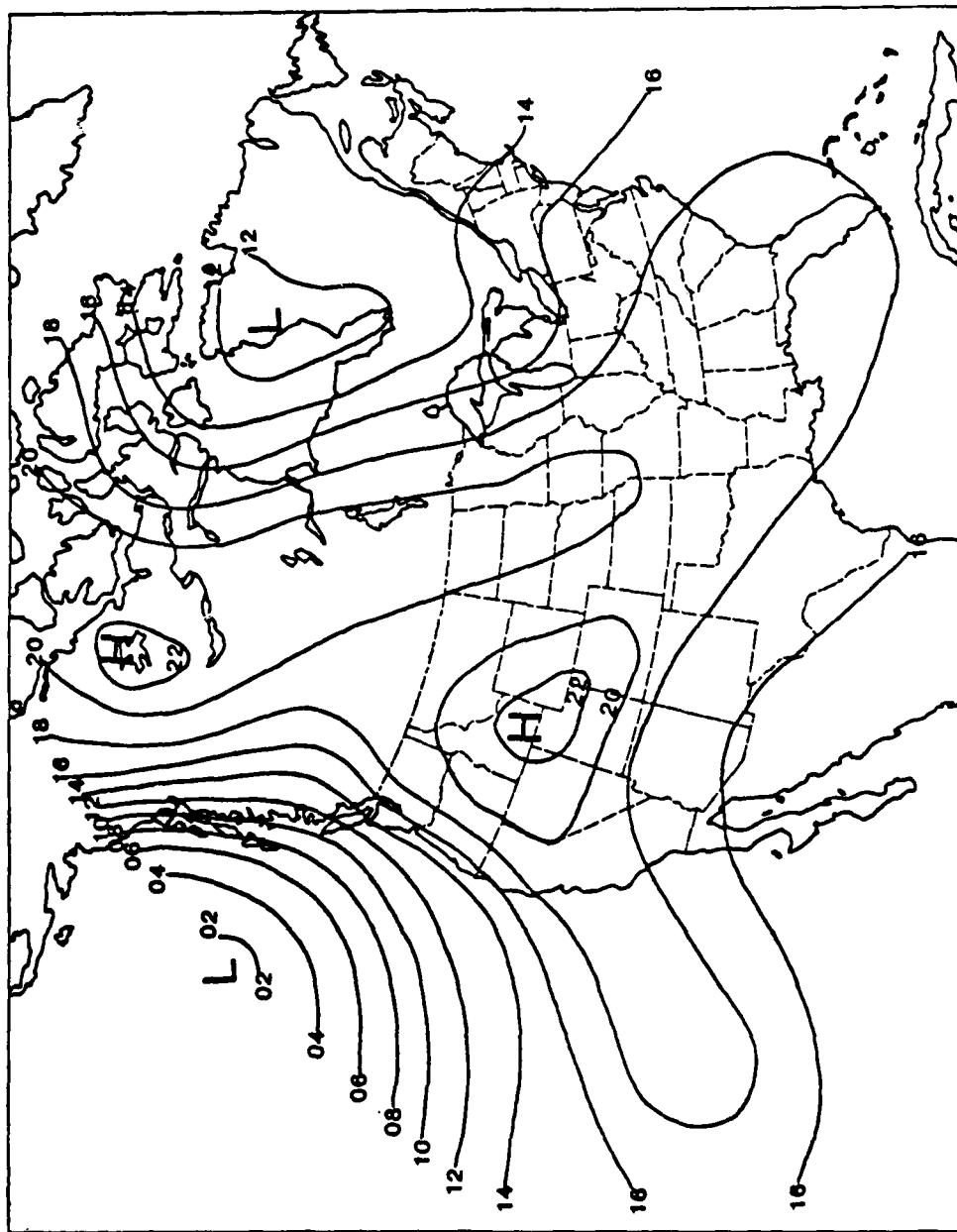


Figure 13. Observed mean sea level pressure for December 1950. December 1950 corresponds to 2620 in the .3868, .7736 cycle.

The time phase, $2\pi(ft)$, is now calculated by setting $f=.1132$ cycles/year. The time phase for .1132 cycles/year in December 1950 is 278.4° . The pressure anomaly map at 278° in the .1132 cycle can be added to the pressure anomaly map using .3868 cycles/year and .7736 cycles/year (Fig. 12j) to get the total anomaly for December 1950 based on all three frequencies. In this case the pressure anomaly pattern determined by .1132 cycles/year does not provide much support for a strong northerly flow over Minnesota, but does reinforce the anomalous high in western Canada (Fig. 12j).

December 1957 was one of the "warm" years referenced earlier that applied to St. Cloud and Minneapolis. This case shows how the frequencies reinforce each other in the warm part of their respective cycles. First, .3868 cycles/year has a time phase of 156° in December 1957. Figure 12f shows an anomalistic Pacific-type flow across the upper Midwest, characteristic of a warmer than normal December. A time phase of 204° for .1132 cycles/year corresponds to a synoptic pattern which reinforces a zonal or even southerly flow pattern across Minnesota. The pressure maps generated by using .1132 cycles/year may reinforce, dampen, or have very little effect on the pressure maps generated by using .3868 cycles/year and its harmonic (Figs. 12a to 12l).

Any of the cold years or warm years which are underlined in Figures 6 and 7 can be examined in this manner. The proper combination of pressure maps is determined by knowing the year to be examined, calculating the time phase for each frequency, then adding

the pressure anomalies of each frequency at their respective time phases to get a total pressure anomaly map. The resulting pressure anomaly map using all three frequencies can synoptically explain that year's temperature anomaly. The temperature anomalies in many of the other years near the regressed values can also be explained by the pressure anomaly maps. There are certainly other forcings taking place which explain the wide scatter in parts of Figures 6 and 7, but this procedure is at least a first step in an effort to synoptically explain some of the variance observed.

Amplitude and phase angle maps for each frequency (Figs. 14a to 16b) help to clarify the large scale synoptic patterns. The largest amplitudes are associated with .3868 cycles/year (Fig. 14a) and .7736 cycles/year (Fig. 15a). All three frequencies have a maximum amplitude in the Northwest Territory of Canada (Figs. 14a, 15a, and 16a). This is a region where changes in pressure data seem to influence a response in temperature data in the north-central United States. The pressure changes in this "forcing region" cause temperature changes in the "response region". A strong high pressure cell centered in northwest Canada forces colder air farther south into the United States, and similarly a strong low pressure cell centered in northwest Canada cuts off Arctic outbreaks. The regressed solution, using .3868 cycles/year and .7736 cycles/year, explains about 26% of the total interannual variance in pressure at 60°N, 130°W (herein called station 108). As pressure fluctuations progress in this cyclic manner, temperature responds in the same

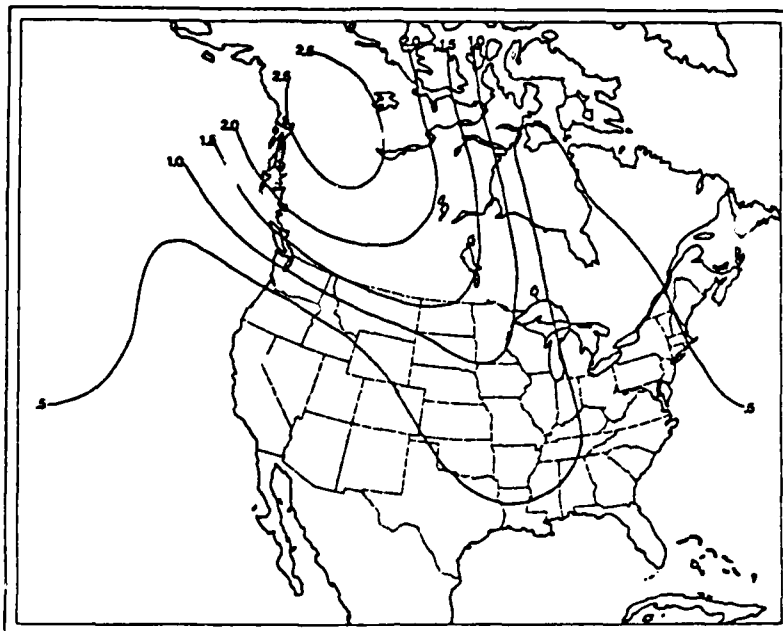


Figure 14a. Pressure amplitude (denormalized) computed from the regression using .3868 cy/yr.

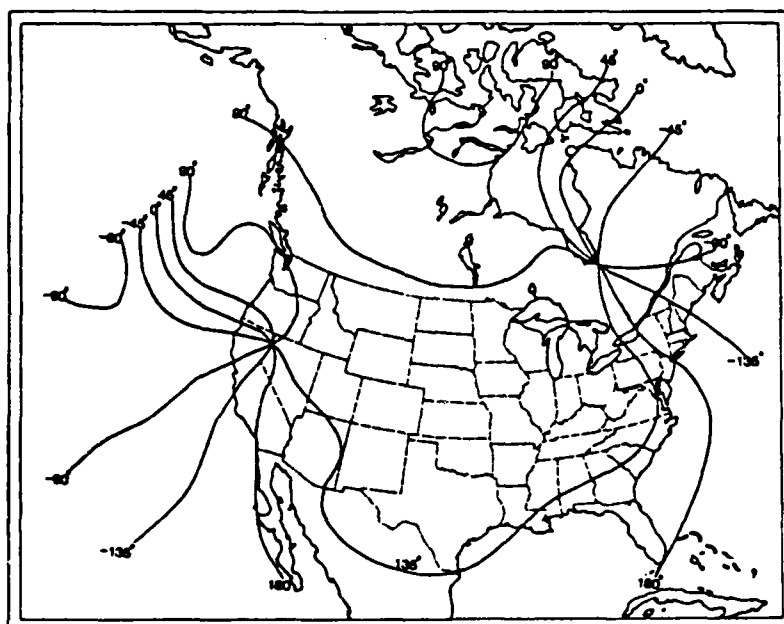


Figure 14b. Pressure phase angle computed from the regression using .3868 cy/yr.

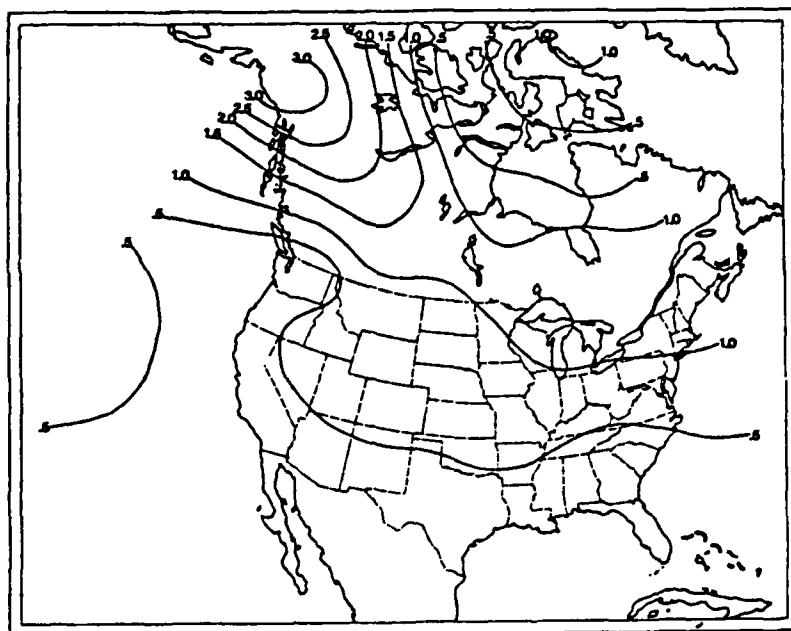


Figure 15a. As in 14a except using .7736 cy/yr.

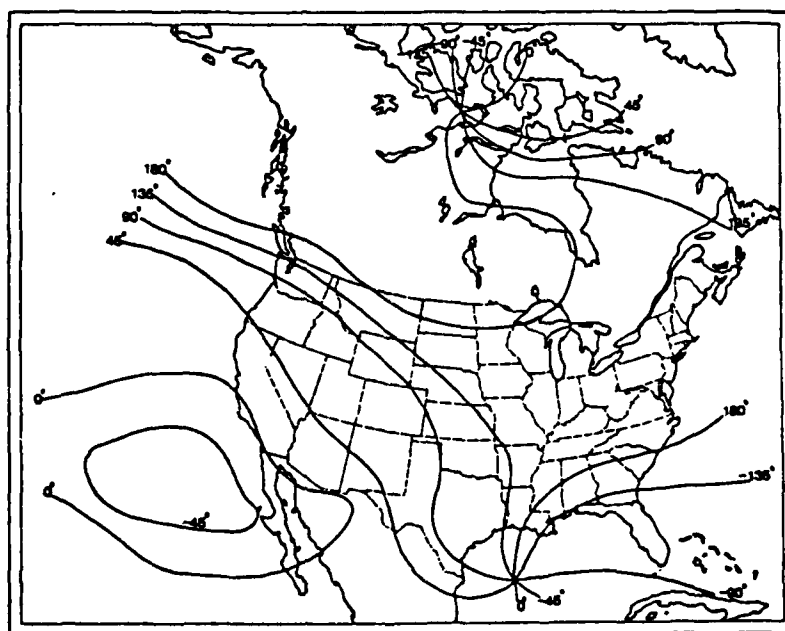


Figure 15b. As in 14b except using .7736 cy/yr.

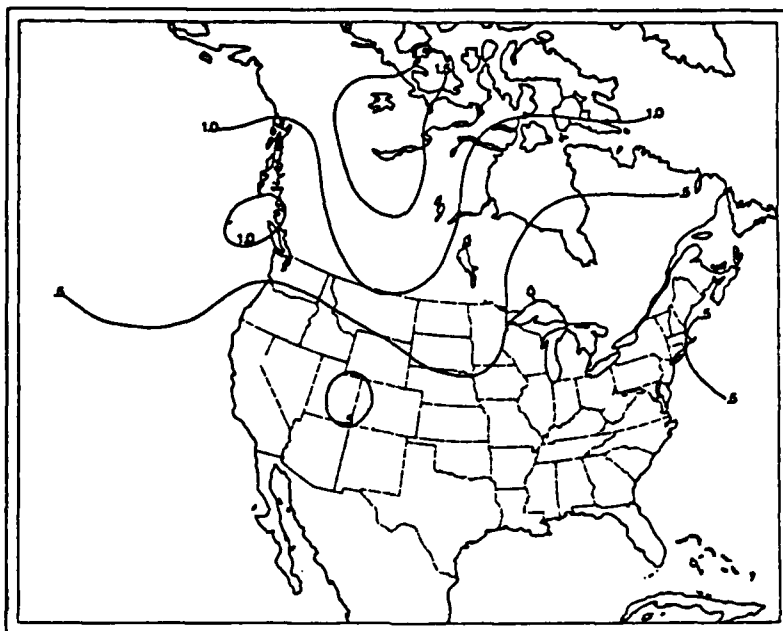


Figure 16a. As in 14a except using .1132 cy/yr.

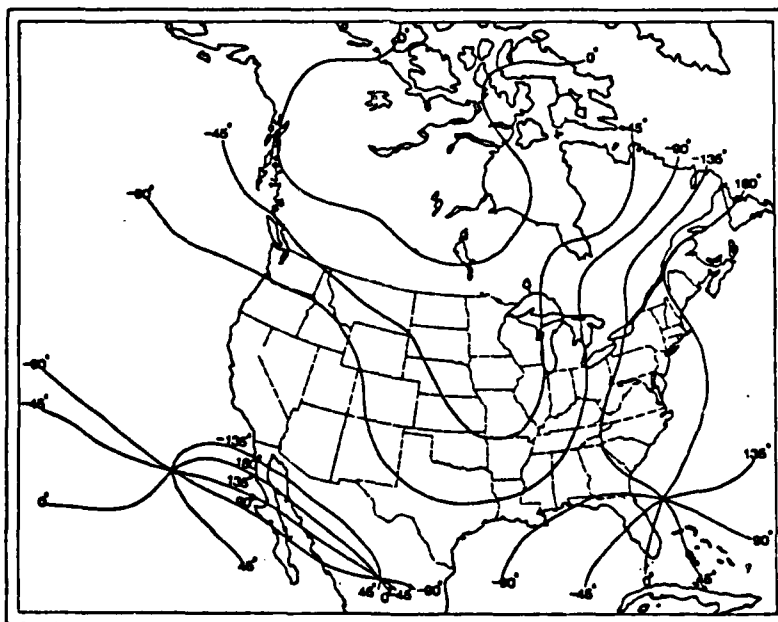


Figure 16b. As in 14b except using .1132 cy/yr.

cyclic fashion. The phase angle maps (Figs. 14b, 15b, and 16b) indicate that the synoptic pressure pattern is generally in phase over most of western Canada extending into the midwest United States. Areas along the east and west coasts of the United States and north of Hudson's Bay are out of phase (180^0) with respect to the region in northwest Canada. This makes sense synoptically, since ridging extending southeast from western Canada should be linked to troughing on either side. This analysis reflects only an anomaly pattern and the actual surface map (anomaly plus mean) may have different characteristics.

The above discussion emphasizes a regional connection between pressure in northwest Canada and temperature in Minnesota. If this is the case, the frequencies in the "forcing region" (pressure data) should closely align with the frequencies in the "response region" (temperature data). Periodograms were calculated for pressure data at 60^0N , 130^0W , and temperature data at St. Cloud. The same period of record, 1899-1978, was used for both cases to minimize inconsistencies in comparing results. In Figure 17 the pressure periodogram (solid line) is superimposed on the temperature periodogram (dashed line). The dashed line in Figure 17 shows three frequency peaks (.1138 cycles/year, .2275 cycles/year, and .3875 cycles/year) in the temperature data analogous to the ones referenced in the 1893-1980 periodogram (Fig. 3). The periodogram of pressure data (solid line) has two peaks, .2275 cycles/year and .3838 cycles/year, corresponding quite well with similar frequencies in the

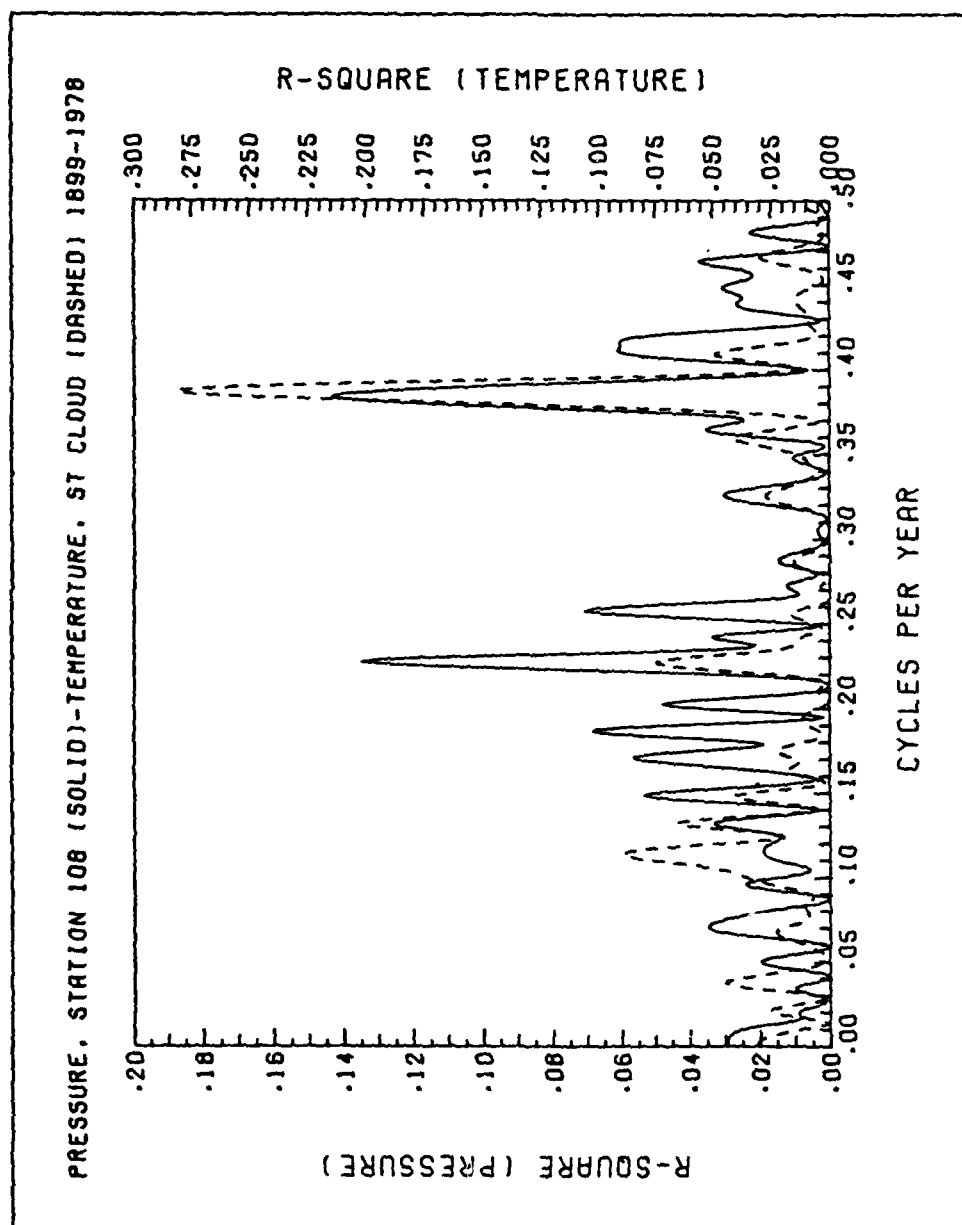


Figure 17. Periodograms (1899-1978) of pressure data (solid) at 60°N, 130°W and temperature data (dashed) at St. Cloud.

temperature data over 2600 km (1600 miles) away. The relationship is not as clear around .11 cycles/year. Sharp frequencies, that are regionally consistent, synoptically reasonable, and stable in time, showing up in both temperature and pressure data can be used with confidence as a forecast tool. Having established the existence of these frequencies in the temperature and pressure data base, and having provided a logical synoptic explanation, the next step is application.

APPLICATION

As mentioned at the onset, the ultimate purpose of this research and its practical application, is to make long range forecasts. The application of periodicities to forecasting in a statistical prediction technique, must meet several conditions (WMO #79, 1966):

- 1) If a statistically significant trend is evident it should be removed before the prediction is made. At St. Cloud trend was not a factor.
- 2) The series to be predicted must contain some form of non-randomness other than trend. This non-randomness may consist of periodicities, quasiperiodicities, persistence or any combination of these. Two sharp periodicities near .39 cycles/year and .23 cycles/year and one possible periodicity near .11 cycles/year have been combined.
- 3) Oscillatory components are additive. This has been done in the analysis.
- 4) Future values of the series are related to past values primarily by linear regression functions. This is the key condition used to obtain the forecast results.

For the initial test, data from 1961 through 1980 were used as an independent set. To use that data as an independent period, the frequencies used to predict 1961-1980 were calculated using only data up to 1960. Forecasts for December temperature were made and verified for this twenty year period across the United States and Canada. The

first forecasts were made using frequencies obtained from the temperature periodogram (1899-1960) for St. Cloud (Fig. 18). This period of record was used so a direct comparison could later be made to a pressure periodogram with the same period of record. The frequencies, .3871 cycles/year, .1113 cycles/year, were selected because of their large explained variance. The peak at .2258 cycles/year was also selected as a predictor because it is the alias frequency of the first harmonic of the extremely large peak at .3871 cycles/year. Using (4), two-by-two skill scores were calculated for 64 stations across the United States and 22 stations in Canada (see Appendix).

$$(4) \quad \text{Skill} = (C-E)/(F-E)$$

C is defined as the number of forecasts correct, E is the number of forecasts expected correct by chance, and F is the total number of forecasts. A skill of .3 would correspond to 13 correct forecasts out of 20. By chance one would expect 10 correct out of 20 for an above normal-below normal type of forecast. A skill of zero means the forecast is no better than what one would expect by chance (i.e. the flip of a coin). Figure 19 shows the two-by-two skill scores obtained by using .3871 cycles/year, .2258 cycles/year, and .1113 cycles/year as predictors of December temperature. The large shaded area extending from west-central Canada into the center of the United States is a region of year-in-advance skill scores which are greater than or equal to .30. The 95% significance using cumulative binomial probabilities (Kirkpatrick, 1974) at a specific station would be represented by skill scores near .32. Using the same test on the

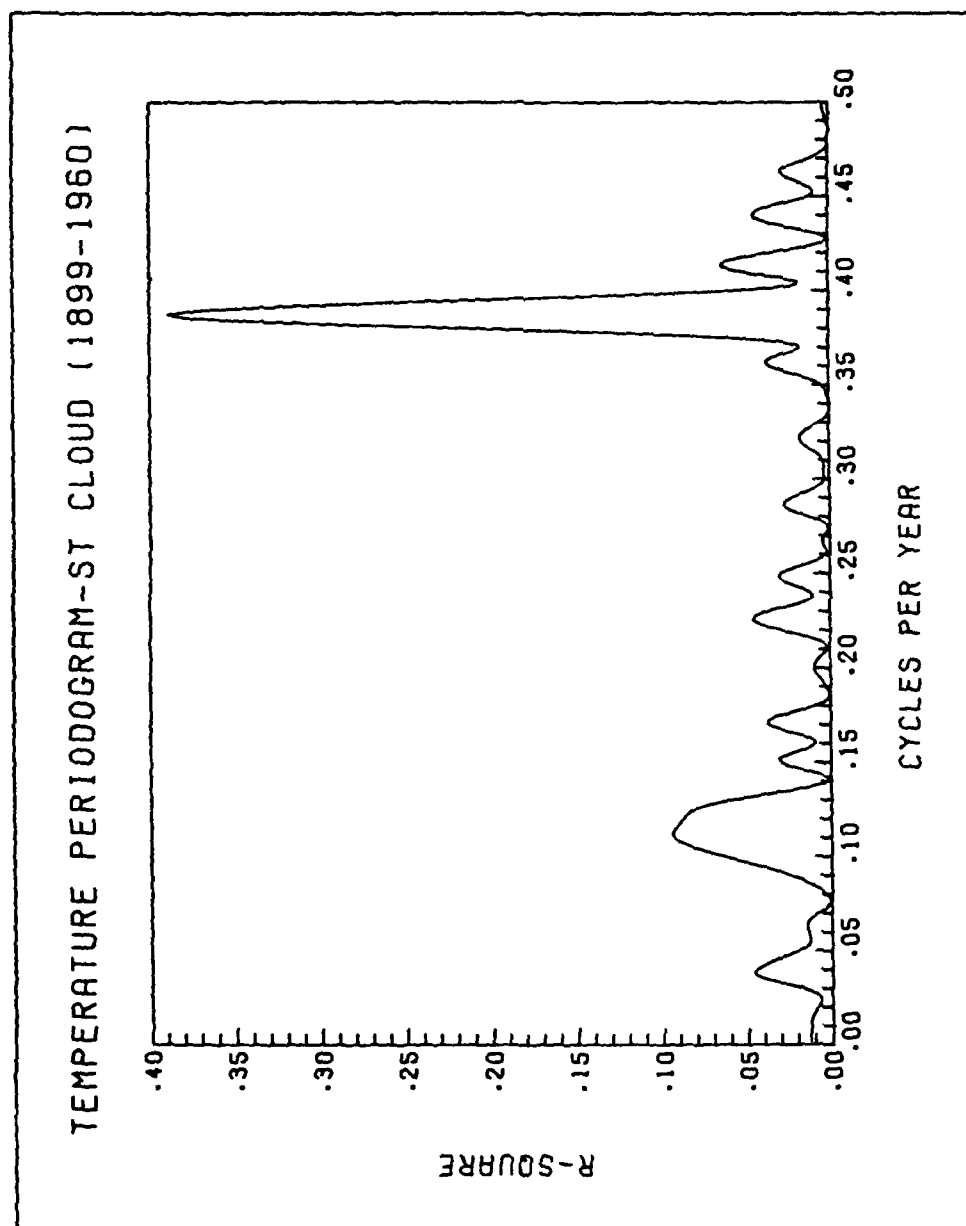


Figure 18. Periodogram of temperature data (1899-1960) at St. Cloud.

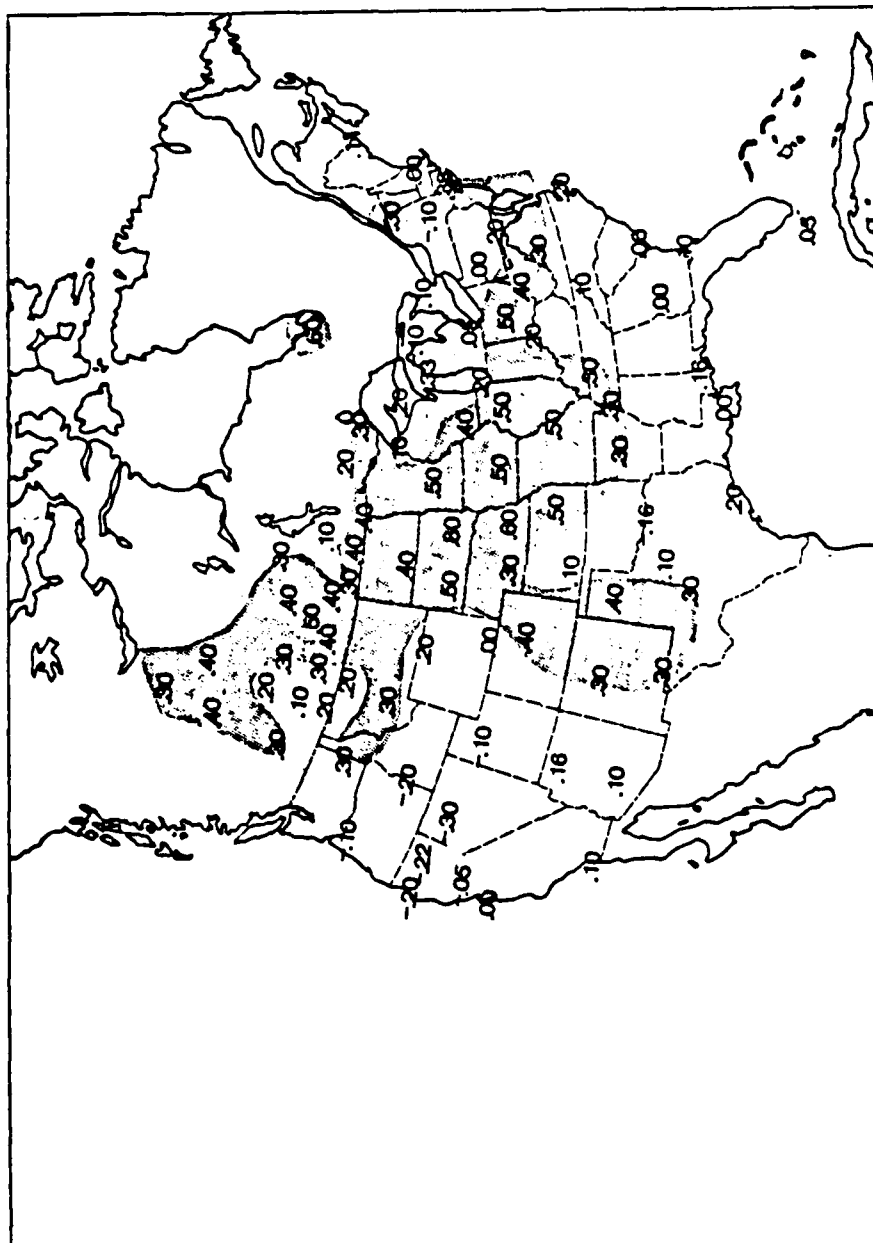


Figure 19. 2 by 2 skill scores of independent forecasts made from 1961 to 1980. Forecasts were made by regression using frequencies (.3871 cy/yr, .2258 cy/yr, and .1113 cy/yr) from the temperature periodogram (Fig. 18). Shaded area represents skill scores of .3 or more.

cumulative number of correct forecasts for the map as a whole (1046 correct out of 1723 trials), there is less than one chance in 10 million that the skill scores (Fig. 19) are random. Because nearby stations are not totally independent of each other, the degrees of freedom were reduced by a factor of ten. This still resulted in a 99.77% significance. The statistical significance is higher when considering only stations located in sensitive regions associated with air mass confluence zones (Fig. 11). In this case 501 correct forecasts were made out of 755 trials and 99.81% significance was obtained by reducing the degrees of freedom by a factor of ten.

Temperature changes are a response to changes in pressure patterns. The largest changes in pressure (amplitude) using these approximate frequencies occur in northwest Canada (Figs. 14a, 15a, and 16a). This area of northwest Canada has been referred to as the "Klondike" source region for Arctic air in the United States (Wendland and Bryson, 1981). Wendland and Bryson stated that December was the only month in which no source region could be identified, in the mean. It appears as though December is transitional from an Ohio Valley source region to a "Klondike" source region which is dominant in January. The timing in December of the transition to a "Klondike" source will determine the temperature pattern for the month in most of the upper Midwest. Therefore, periodic pressure fluctuations in this region may control air mass movement. Since northwest Canada seems to be a "forcing region" with large amplitudes associated with the three frequencies used, a periodogram was calculated on pressure data for

station 108 from 1899-1960, so 1961 through 1980 could again be treated as independent years for forecast verification. The frequencies selected as good predictors from the pressure periodogram should be similar to the frequencies in the temperature data. Thus the selection was made assuming that a synoptic or physical link connects pressure changes in northwest Canada and temperature changes in the north-central United States. Using the periodogram (Fig. 20) the frequencies .3839 cycles/year, .2242 cycles/year, and .1274 cycles/year were selected as the best predictors that would correspond to the frequencies in the temperature data. The frequencies from the pressure data were then used to make 20 years of temperature forecasts for December. These results are shown in Figure 21.

The results in Figure 21 statistically represent a 99.999973% probability (965 correct out of 1723 trials) that the map of skill scores was not generated by a random process. Significance is reduced to 94.55% by again reducing the degrees of freedom by a factor of ten. The pattern of skill scores greater than or equal to .30 in Figure 19 compares favorably to that in Figure 21. It is noteworthy that this area of highly significant forecastability lies in the midst of a region suggested by Barnett (1981) as being a region of maximum "noise" and minimum predictability.

The areas of poor or marginal skill seem to be influenced by the mountains to the west, the Gulf of Mexico and Atlantic to the south and east, and certain areas around the Great Lakes. Geographic features and synoptic patterns may work together to alter or reinforce

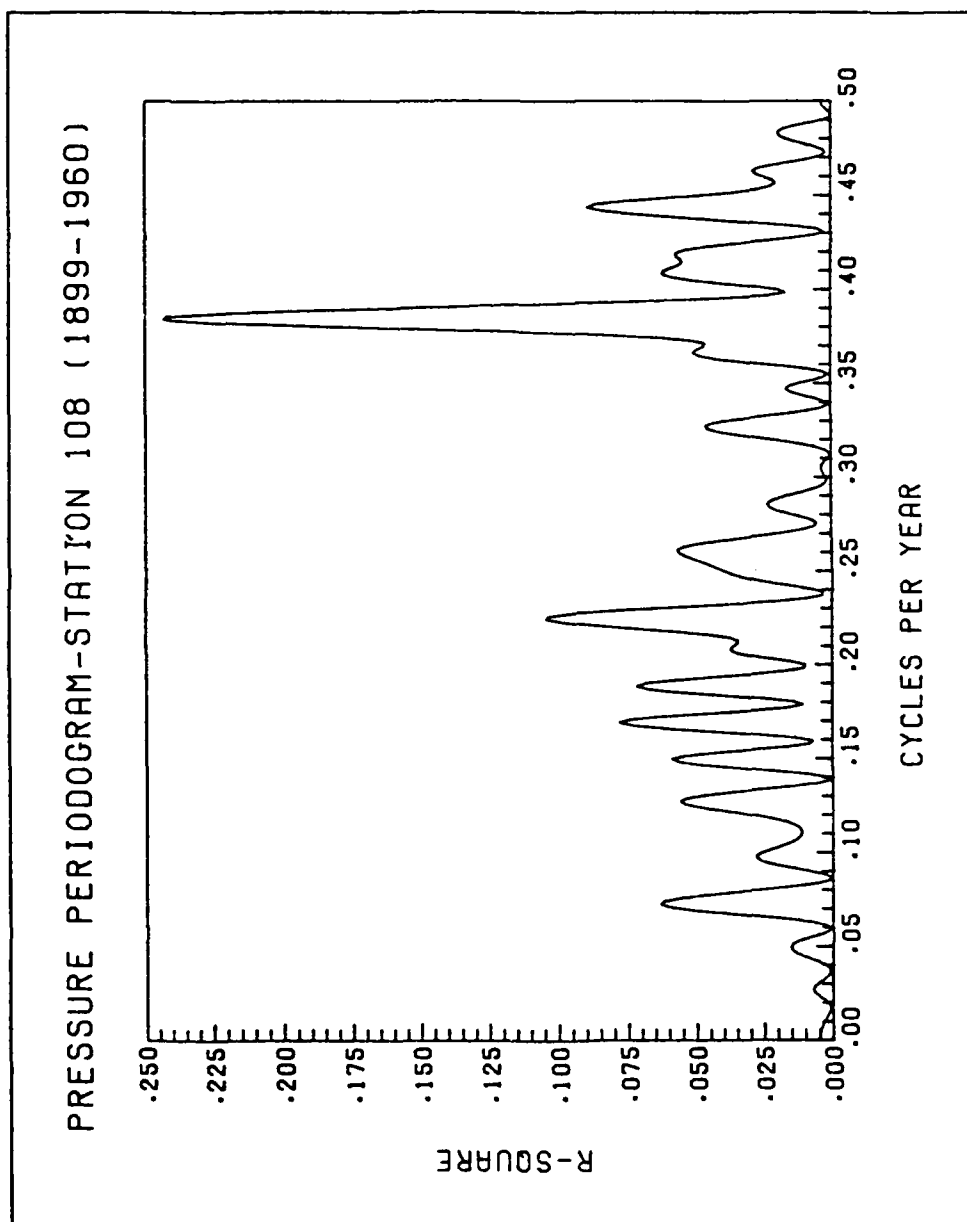


Figure 20. Periodogram of pressure data (1899-1960) at 60°N, 130°W.

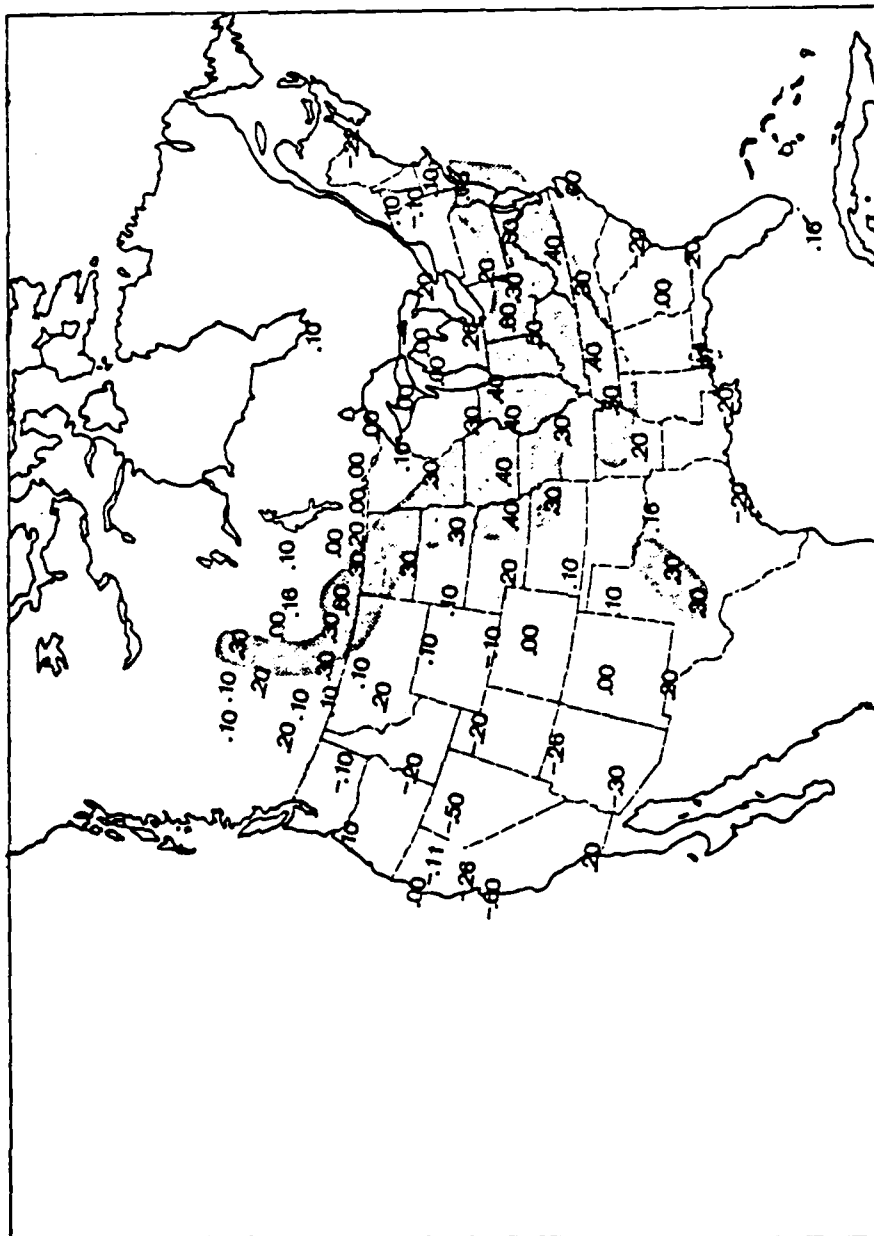


Figure 21. 2 by 2 skill scores of independent forecasts made from 1961 to 1980. Forecasts were made by regression using frequencies (.3839 cy/yr, .2242 cy/yr, and .1274 cy/yr) from the pressure periodogram (Fig. 20). Shaded area represents skill scores of .3 or more.

the pattern of skill scores. For example, the location of mountains will alter the movement of cold air originating from the "forcing region" and the strength of the cold air outbreak will shift the mean frontal positions. The biggest effect of such a shift will be in the area most sensitive to slight changes in the mean frontal position (Fig. 11). This mean frontal position may be oscillating at these frequencies with enough predictability to provide good skill scores in regions sensitive to small dislocations of the mean front.

The pattern of skill scores based on frequencies from the pressure data seem to geographically fit the position of the mean fronts even better than the pattern of skill scores from the temperature data. Thus, pressure changes are linked to changes in synoptic patterns which force temperature changes in sensitive areas. This seems to be occurring at the three frequencies already examined or approximations to these frequencies. The forecasts made by applying these frequencies to temperature and pressure data (Figs. 19 and 21) showed a regional pattern of good skill scores, suggesting forecasts using either technique or a combination of both would provide usefully accurate forecasts for a region sensitive to these frequencies. Specifying more exact frequencies by using the nonlinear regression technique did not produce overall improvement to the skill scores in Figures 19 and 21. The forecasting technique requires frequencies specified to the third decimal place though, and it seems beneficial to select frequencies which show up in temperature and pressure data. This insures a physically justified regional model.

Long range forecasts of pressure patterns is another practical application. Since the assumption throughout has been a link between pressure and temperature, the forecast of temperature and pressure patterns must be internally consistent. Having already made temperature forecasts, pressure map forecasts can logically follow. December 1981 was forecast to be a cold month, well below normal for St. Cloud and, using regional consistency (Fig. 21), much of the upper Midwest and Ohio Valley. The forecast pressure pattern should explain these below-normal temperature forecasts. An analysis of December 1981 is presented to demonstrate the application of the pressure forecast procedure. December 1981 has a specific time phase, $2\pi(ft)$, for each frequency. For .3868 cycles/year its phase is 258° , for .7736 cycles/year it is 156° , and for .1132 cycles/year it is 102° . Figure 6 gives a first indication of the forecast temperature for December 1981. This regression, using only .3868 cycles/year and .7736 cycles/year with the time scale based on .3868 cycles/year, shows 1981 to be at 258° on the regressed curve. This is near the bottom of the curve indicating a much below normal temperature pattern for central Minnesota. The forecast pressure anomaly pattern to explain this cold temperature anomaly is shown in Figure 22. This pressure anomaly pattern was constructed by adding the effects of each frequency. The primary pattern of the anomaly field was determined by .3868 cycles/year and its harmonic, .7736 cycles/year. Figure 22 indicates an unusual amount of northerly flow based on a regression of the pressure data using all three frequencies. By adding the pressure

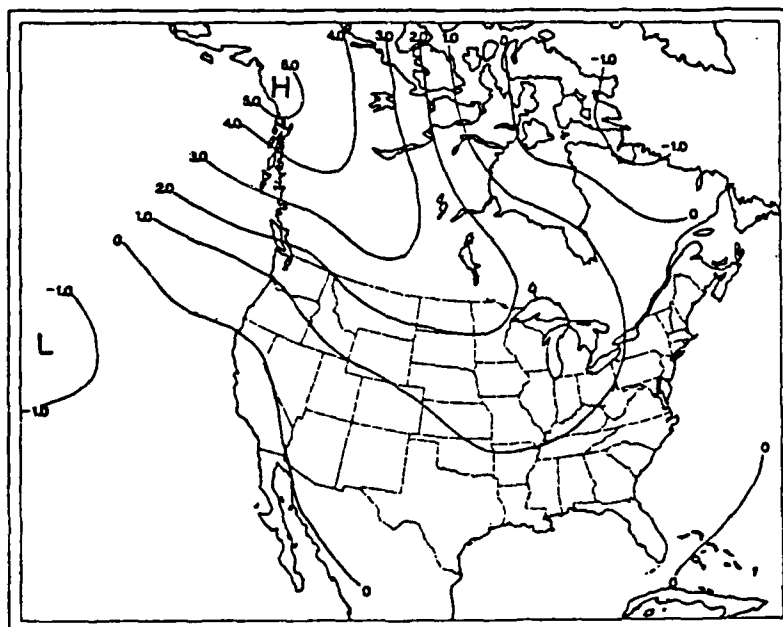


Figure 22. Anomalies using pressure data regressed against .3868 cy/yr, .7736 cy/yr, and .1132 cy/yr. Anomalies are additive at the respective time phases (258° , 156° , and 102°) of each cycle. These time phases correspond to December 1981.

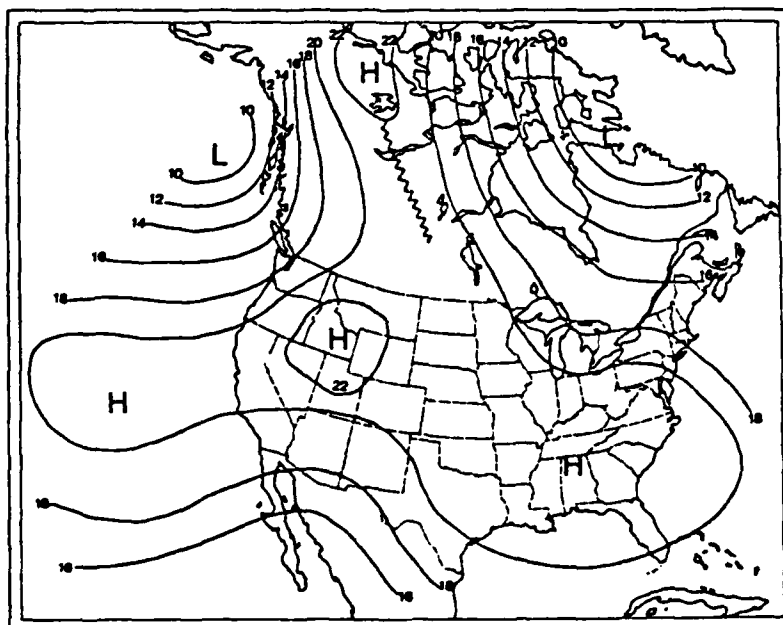


Figure 23. Forecast pressure map for December 1981 obtained by adding the mean pressure map (Fig. 9) and the anomaly map (Fig. 22).

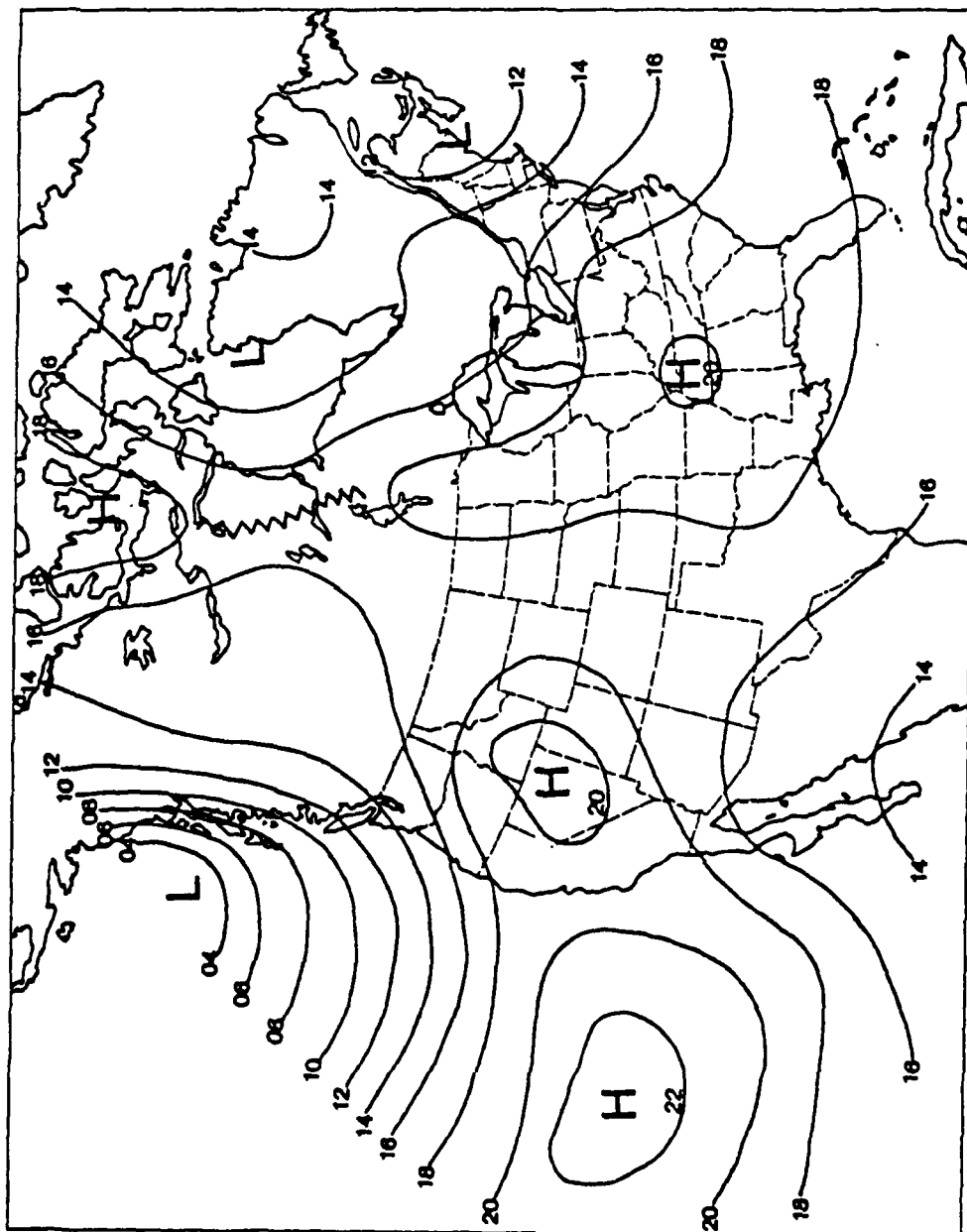


Figure 24. Observed mean sea level pressure for December 1981.

anomaly pattern, Figure 22, to the mean December pressure pattern. Figure 9, the result is a forecast pressure map for December 1981 (Fig. 23). Notice the similarity between the forecast 1981 map (Fig. 23), and the observed 1950 map (Fig. 13). Both years are very close to the same place in the cycle. December 1950 was at 262° and December 1981 was at 258° in the cycle. The verification of December 1981 provides further information concerning the accuracy of this single test (Fig. 24). Although a large contribution to the observed pressure pattern is a result of the mean map, the forecast did catch the ridging extending from central Canada into Minnesota. The connection of the ridge from Canada to the southeast United States, versus a zonal flow across the upper Midwest, is the key feature that is captured by this pressure map forecast procedure. On the observed data this ridging was displaced to the east of the forecast position and was weaker than predicted. St. Cloud's -1.1°C departure from normal for December 1981 can in part be explained by the observed synoptic pressure pattern, and the forecast pressure pattern was a persistent one which dominated January 1982. Obviously a large number of independent years should be examined to determine the real accuracy of this pressure map forecast method. This example was only provided to demonstrate the potential of this procedure, but was done in real-time during the writing of this thesis.

DISCUSSION

This study would not be complete unless a suggested link existed between some physical forcing mechanisms and the frequencies observed in the temperature and pressure data. The atmosphere is a fluid 1000 times less dense than the oceans. There is substantial evidence that lunar forces affect the ocean, for this is what generates tides. It seems reasonable to assume that forces influencing one fluid body must also be acting on an adjacent fluid body, and in the atmosphere these lunar forces have been shown to affect the polar fronts (Mills, 1966). There is also evidence to suggest that there are other external forcing mechanisms (Mitchell, 1976) acting on our earth, ocean, atmosphere system. One of these external forces, the Chandler tide or pole wobble, has been shown to generate certain frequencies in meteorological data (Bryson and Starr, 1977), as well as oceanic data (Lisitzin, 1974). It is reasonable to expect a nonlinear response and in such a system harmonics may be important. If so, the spectra of the response would be hard to interpret. One of the fundamental Chandler frequencies cited in the Bryson and Starr paper was .807 cycles/year. The first harmonic of .807 cycles/year is 1.614 cycles/year. Applying the Nyquist frequency to annual sampling ($1/2\Delta t = .5$ cy/yr) results in high harmonics which will alias or fold over to show up at lower frequencies, less than .5 cycles/year. Using (5), where f_a is the alias frequency and f_h is any high frequency greater than the Nyquist frequency with integer cycles removed, the

higher frequency (greater than .5 cycles/year) can be calculated to show up as an alias in these lower frequencies (Bryson and Starr, 1976).

$$(5) \quad f_a = (1/\Delta t - f_h)$$

If this assumption is correct, 1.614 cycles/year will show up in the spectrum at .386 cycles/year (Fig. 1). By reversing this logic, the frequency found in the temperature record at St. Cloud, .3868 cycles/year, if a harmonic, would be equivalent to .8066 cycles/year, very close to a fundamental Chandler frequency. Similar reasoning indicates that the fourth harmonic of .8066 cycles/year equals 3.2264 cycles/year. This shows up in the lower frequencies at .2264 cycles/year, almost exactly where the second strong peak in the temperature periodogram of St. Cloud is observed at .2263 cycles/year (Fig. 3 and Table 2). These two frequencies, .3868 cycles/year and .2263 cycles/year, appear to have a solid link to a physical forcing. The Chandler motion produces a small displacement of parts of the climatic pattern and it would appear logical to examine the record in areas where slight displacements produce significant changes (Bryson and Starr, 1976). This hypothesis used by Bryson and Starr seems to apply equally well to the case presented here.

Matsukura (1965) presented additional evidence linking actual circulation and synoptic changes to pole tide movements. There appears to be a close connection between the variation of general circulation and the polar motion, and the general circulation and polar motion have an interaction with each other. Since the polar

motion exerts such an influence on the general circulation over the Northern Hemisphere, it is logical to conclude that south and northward transport of Arctic air masses is also greatly influenced by the pole tide (Matsukura, 1965). Matsukura found that the longitude of polar outbreaks varied with the first harmonic of the pole frequency. This distribution of air masses being influenced by polar motion will obviously have an effect on temperature and pressure data. This helps to explain why Chandler frequencies might be observed in certain meteorological records.

If these forcings are influencing the atmospheric pressure patterns the general effects are suggested by the cycle of pressure anomalies (Figs. 12a to 12i). An obvious center of action has been observed in northwestern Canada. A strong low pressure anomaly exists there at 150° phase (Fig. 12f) versus a high pressure anomaly at 270° phase (Fig. 12j). When these extreme pressure anomalies in the cycle are each added to the mean map (Fig. 9), there seems to be a pattern of oscillation of intensity or position of the Icelandic low versus the Aleutian low (Fig. 25 versus Fig. 26). In Figure 25 ($.3868 \text{ cy/yr} + .7736 \text{ cy/yr}$, at 270°) the Icelandic low has intensified or shifted southward, with a strong east west pressure gradient across eastern Canada. The Aleutian low is weaker and displaced westward. A strong high dominates west-central Canada. This part of the cycle corresponds to the cold temperatures observed at St. Cloud (Fig. 6, 240° to 300°). By comparison, in Figure 26 ($.3868 \text{ cy/yr} + .7736 \text{ cy/yr}$, at 150°) the Aleutian low now dominates with a weak trough

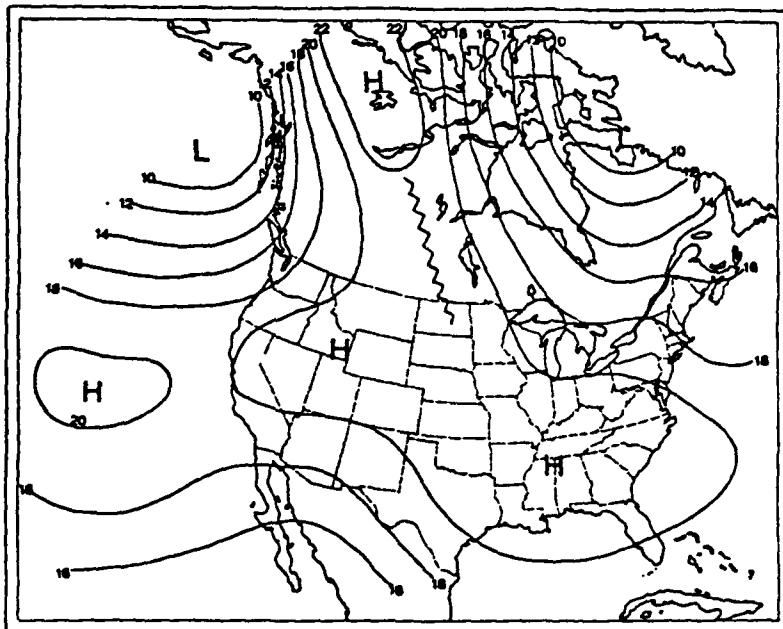


Figure 25. Pressure map (anomaly plus mean) calculated from regressions using .3868 cy/yr and .7736 cy/yr. Time phase is at 270° , corresponding to the cold part of the cycle (see Fig. 6).

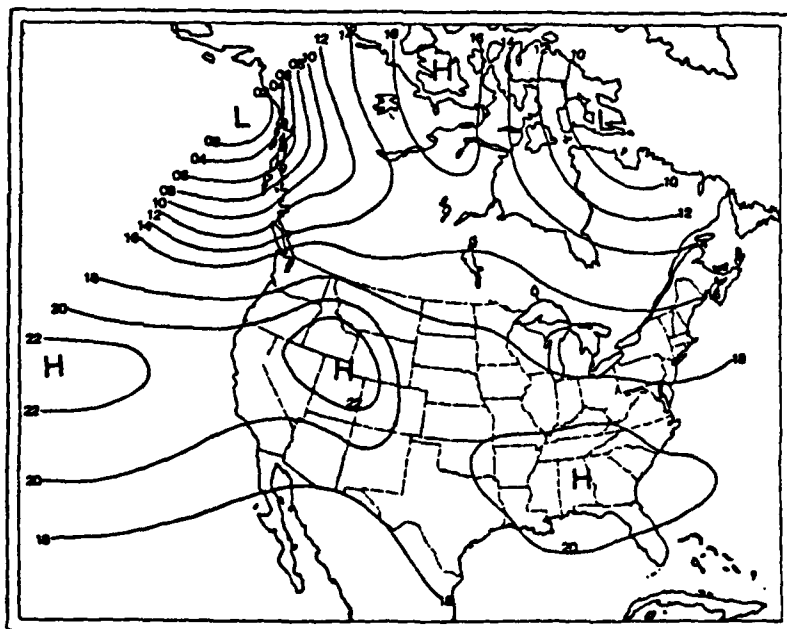


Figure 26. As in Fig. 25 except in the warm part of the cycle at a time phase of 150° .

across western Canada. The high weakens and relocates over north-central Canada, and the gradient in eastern Canada has weakened. This zonal flow pattern delivers mild air to the upper Midwest as seen in Figure 6, 120° to 180° in the cycle.

The ridge over western Canada and the trough over eastern Canada tend to fluctuate in position east to west in relation to the pole tide (Matsukura, 1965). This small cyclic change in the Aleutian and Icelandic low pressure patterns, and the high in between, may be just enough of a change to synoptically influence a sensitive region like the upper Midwest and provide a temperature record which shows the signal of this cyclic pattern. Other work has shown that the highest variability of winter mean sea level pressure corresponds closely to the location of the Icelandic and Aleutian lows (Blackmon et al, 1977). These three frequencies may help to explain some of this variance.

Additional evidence from Bryson and Lahey (1958), corroborates the above discussion. December has been observed to be a month when the position of the Aleutian low shifts. In autumn the low is located over the Gulf of Alaska. This would most likely be associated with more zonal, mild, flow (analogous to Fig. 26). During December the low shifts positions and relocates, in its winter position, over the Aleutians. This allows strong ridging to occur over the western United States and Canada with the possibility of cold Arctic outbreaks (analogous to Fig. 25). This shifting may be occurring in a periodic fashion associated with the Chandler tide. The evidence presented in

this study supports a physical cause related to the observed frequencies. If the observed frequencies are strong and have justifiable physical links, a forecast using these periodicities is also justified. The actual application of Chandler tide to forecasting has been incorporated in a climate model (Bryson, 1978). Regional evidence of the Chandler periodicities in temperature and pressure data, and good skill scores in a synoptically sensitive region, offers additional support that these periodicities may be a useful forecast tool for December as well.

SUMMARY

Periodic behavior of December temperature time series in the United States and Canada has been examined. Significant power, possibly associated with Chandler tide periodicities, was centered over central Minnesota, where about 40% of the interannual December temperature variance is explained by three frequencies. Time and area sensitivities to these three frequencies were discussed. December is a climatically sensitive month as basic synoptic patterns undergo a transition from fall to winter. The area of North America most sensitive to these three frequencies lies along or near mean air mass boundaries or confluence zones. The synoptic explanation of the strong periodic behavior of the temperature data was investigated by regressing pressure data against a set of frequencies observed in temperature data. The pressure anomaly maps provided the basis for determining what synoptic patterns are associated with certain temperature anomaly patterns. Cold years corresponded to anomalous northerly flow and warm years corresponded to anomalous zonal flow. The flow pattern was controlled by periodic changes of the pressure pattern. This internal consistency between temperature and pressure, and the similarity in periodicities found in the temperature and pressure spectra, provided justification to proceed with a forecast experiment. Forecasts and verifications were made for twenty years of independent data. The region of climatic sensitivity to the three frequencies corresponded well to the area showing high skill scores.

Thus, similar frequencies obtained from different data sets of temperature and pressure can be used to create a regional forecast model. One is led to conclude that the three dominant frequencies observed in temperature and pressure data (near .39 cycles/year, .23 cycles/year and .11-.13 cycles/year) are not random and they may be related to an external forcing mechanism, possibly the pole tide. The frequencies have regional consistency and temperature and pressure data analyzed using these frequencies are synoptically coherent. Using these periodicities as predictors has proven useful for making skillful year-in-advance forecasts on independent data.

More work must be done on generating forecast pressure maps using these techniques. Only a sample procedure was presented in this study. This approach might provide a regionally and synoptically consistent, long range forecast for pressure, temperature, and precipitation. Further research should focus on applying these techniques to other months and developing other regional models. The results for December 1981 and the following very cold January 1982, raise questions concerning the persistence and precise timing of this forcing. More detailed analysis relating December's forecast to January should be examined since December may be a pivotal month in determining the character of the winter. Rigorous statistical and theoretical techniques must be applied to the cause and effect relationship (e.g. mechanical pole tide forcing and frequencies observed in temperature and pressure data). A thorough study of the years where temperature anomalies were not explained by the

frequencies used here might provide insight into other predictive thermal or mechanical forcing mechanisms. Certainly other forces affect temperature and pressure patterns, otherwise there would be no variations left in the data. The ultimate goal would be to explain all the variability. Making physical interpretations of the temperature and pressure fluctuations at these frequencies is difficult because of modulation of the frequencies by each other or by other forcings, changes in amplitude of a single frequency with time, different periods of record, nonlinear responses, and inherent aliasing problems. Geographic questions remain concerning the weakness of this procedure near the Great Lakes where modification of an air mass may hide the signals. Temperature patterns may also be altered by variations in snow cover from year to year. It is also possible that the forcings assumed to be Chandler tides may actually be lunar forces or the interaction of the two.

Most research raises more questions than it solves, but the main issue left for future resolution is....Will the time come when extremely accurate long range forecasts can be made? Will the forecasts be based on periodicities which explain much of the variance, and will these periodicities be related to mechanical and thermal forcing mechanisms?

APPENDIX

The variance spectrum was calculated using a Fast Fourier Transform (FFT) technique. This type of harmonic analysis decomposes large sets of normalized data into periodic components, even if periodicities do not seem to be apparent. The j^{th} Fourier frequency is defined by, $f_j = j/N$, where j equals the number of bands or cycles and N equals the total number of years. Only frequencies less than or equal to half a cycle per data interval are considered. This is related to the problem of aliasing. The number of cycles corresponds to $j = 1, 2, 3, \dots, N/2$. Therefore if $N = 88$ (1893-1980) the maximum value for j is 44 cycles and f_{44} equals .5 cycles/year.

Given an 88 year December temperature record, sine and cosine curves are fitted for all frequencies (f_j). The fitted series is represented by (A 1).

$$(A\ 1) \quad T_t = \bar{T} + \sum_{j=1}^{N/2-1} [A_{1j} \cos(2\pi f_j t) + A_{2j} \sin(2\pi f_j t)] + A_{1N/2} \cos \pi t$$

In (A 1), $t = 1, 2, 3, \dots, N$ and \bar{T} equals 0 because the data have been normalized. The FFT method used to solve (A 1) consists of simultaneously solving 88 equations with 88 unknowns (44 cosine terms, 43 sine terms, and the mean) to obtain A_{1j} and A_{2j} by least squares. This series of temperature values can therefore be represented as a sum of periodic components. The harmonic analysis

decomposes the December temperature series (88 years) into frequency components which are repeated an integer number of times (harmonics) in the span of the data (Bloomfield, 1976). Each band is independent (i.e. no variance is shared) so the total variance adds up to 100% in a normalized data set.

The periodogram applies linear regression to (A 1), but solves for each frequency band separately. This simplifies (A 1) into the form of (A 2). When the periodogram solves for integral bands of the same number as the FFT spectrum (44 bands) the calculated variance at each frequency is the same. The total variance does not add up to 100% in the periodogram (except at integral bands) due to some shared variance between nonindependent frequencies. In this periodogram analysis, the number of frequency bands was arbitrarily increased by a factor of 10 so the periodogram solved 440 separate regressions using (A 2).

$$(A\ 2) \quad T_t = \bar{T} + A_1 \cos(2\pi ft) + A_2 \sin(2\pi ft)$$

\bar{T} is again equal to zero and f corresponds to the 440 separate frequency bands. Thus, (A 2) is solved for A_1 and A_2 over the period of record. A_1 and A_2 can then be used to compute the normalized amplitude (A 3) or the denormalized amplitude (A 4), and the phase angle (A 5), for a given frequency (Bloomfield, 1976).

$$(A\ 3) \quad \text{Amplitude (A)} = (A_1^2 + A_2^2)^{1/2}$$

$$(A 4) \text{ Denorm. Amp. (B)} = [(A_1 \sigma_T / \sigma_{\cos})^2 + (A_2 \sigma_T / \sigma_{\sin})^2]^{1/2}$$

$$(A 5) \quad \text{Phase Angle } (\phi) = \begin{aligned} &\text{ARCTAN } (-A_2/A_1) && \text{for } A_1 > 0 \\ &= \text{ARCTAN } (-A_2/A_1) - \pi && \text{for } A_1 < 0, A_2 > 0 \\ &= \text{ARCTAN } (-A_2/A_1) + \pi && \text{for } A_1 < 0, A_2 \leq 0 \\ &= -\pi/2 && \text{for } A_1 = 0, A_2 > 0 \\ &= \pi/2 && \text{for } A_1 = 0, A_2 < 0 \\ &= \text{arbitrary} && \text{for } A_1 = 0, A_2 = 0 \end{aligned}$$

The explained variance (R-Square) accounted for by the frequencies used in the text was calculated from normalized data. The variance explained by a given frequency can be expressed as a ratio of the variance of the regressed values to the variance of the observed values. Since each frequency is independent, variance of several frequencies used together can be added. The variance can also be expressed in terms of the amplitude as shown in (A 6).

$$(A 6) \quad \text{R-Square} = A^2/2$$

Normalizing the cosine and sine functions from (A 1), introduces a $\sqrt{2}$ factor which when squared to obtain the variance, cancels the 1/2 in (A 6). Thus, explained variance for normalized data is simply the square of the normalized amplitude.

(A 7), using the computed amplitude, A, and phase angle, ϕ , from (A 3) and (A 5), is equal to (A 2).

$$(A 7) \quad T_c = \bar{T} + A \cos(2\pi f t + \phi)$$

Similar versions of (A 7) are found in (1), (2) and (3) of the text. (A 2) through (A 7) or slight variations of them are the basic linear regression equations used in the periodogram analysis, and in the sections on temperature and pressure analysis.

UNITED STATES STATIONS

Key West
Jacksonville
Charleston
Macon
Mobile
New Orleans
Galveston
Paris
San Angelo
Abilene
El Paso
Phoenix
San Diego
Cape Hatteras
Asheville
Nashville
Memphis
Little Rock
Amarillo
Albuquerque
Grand Canyon
Washington D.C.
Lynchburg
Cincinnati
Parkersburg
Columbus
St. Louis
Dodge City
Topeka
Denver
Sacramento
San Francisco
New Haven
Blue Hill
Albany
Pittsburgh
Peoria
Chicago
Detroit
Des Moines
Lincoln
North Platte
Cheyenne
Salt Lake City
Winnemucca
Eureka
Mount Shasta

UNITED STATES STATIONS

Eastport
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Alpena
Madison
Traverse City
Huron
St. Cloud
Rapid City
Sheridan
Boise
Portland
Marquette
Duluth
Bismarck
Helena
Havre
Spokane

CANADIAN STATIONS

Toronto
Thunder Bay
Banff
Moosonee
Kenora
Winnipeg
Dauphin
Brandon
Estevan
Regina
Saskatoon
The Pas
Prince Albert
Swift Current
Vermilion
Medicine Hat
Lethbridge
Calgary
Edmonton
Fort Vermilion
Fort McMurray
Beaverlodge

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